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THE EFFECT OF THE SPATIAL POSITION OF A CONTROL ON
THE STRENGTH OF SIX LINEAR HAND MOVEMENTS

Lee S. Caldwell, Ph.D.

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Author

Lee S. Caldwell, Ph. D.

Psychophysiologist
Psychomotor Branch
Psychology Division

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ABSTRACT

THE EFFECT OF THE SPATIAL POSITION OF A CONTROL ON THE STRENGTH OF SIX LINEAR HAND MOVEMENTS

OBJECT

To determine the effects of the distance, angular elevation, and lateral position of an isometric control on the strength of six linear hand movements.

RESULTS

The control distance exerted a stronger influence on the output of the operator than did either of the other spatial variables. The up, down, left, and right movements were strongest at the near control positions and decreased progressively as the distance of the control was increased. Pull increased in strength as the control distance was increased to its maximum, but push increased with distance to the 20-inch position and then decreased as the distance was made greater.

The angular elevation of the control had no significant effect on the up and right movements. Down and push were strongest at the intermediate elevations, left was strongest at the lowest elevation, and pull was strongest at the highest and lowest elevations.

The lateral position of the control had no appreciable effect on the up and pull movements. Left and right were strongest when the handle was directly in front of the shoulder; but down and push were strongest when the control was at the 30° lateral positions.

The mean strengths of the movements in order of magnitude were as follows: push, 103 pounds; pull, 82 pounds; down, 58 pounds; left, 32 pounds; up, 28 pounds; and right, 21 pounds. There was some overlap in the data for the various movements so that the order of preference for the movements will be dependent on the position of the control. The down movement tended to be stronger than either push or pull when the handle was 16 inches or less from the shoulder and at or above shoulder height. At the same elevations up was stronger than left when the handle was at a distance of 24 inches or more.

The data were analyzed by means of the method of orthogonal polynomials and equations were obtained which express the effects of the spatial variables and their interactions on the strength of each movement. The equations may be used to determine the optimal and permissible locations of a force-operated control whose characteristics are known; or they may be used to determine the necessary characteristics of a control at any design-preferred location.

APPROVED: _Ernest K Montague_

ERNEST K. MONTAGUE, Ph.D.
Lt Colonel, MSC
Director, Psychology Division

APPROVED: _Floyd A. Odell_

FLOYD A. ODELL, Ph.D.
Technical Director of Research

APPROVED: _Harold W. Glascock Jr._

HAROLD W. GLASCOCK, JR.
Colonel, Medical Corps
Commanding

THE EFFECT OF THE SPATIAL POSITION OF A CONTROL ON THE STRENGTH OF SIX LINEAR HAND MOVEMENTS

I. INTRODUCTION

As machines are made more complex, and especially as the number of force-operated controls is increased, there also results an increasing need for information regarding the force-generating abilities of the men who are required to operate such controls. With the use of power-assisted controls, it may appear that the physical limitations of the operator are no longer serious barriers to be overcome in the design and operation of such equipment. To an extent this is true, but it is also true that the addition of most power-assisted controls to mechanized equipment (i. e., the addition of power-brakes, power-steering, etc.) is made at a price of increasing weight and bulk, of reducing work space, and of creating new problems of maintenance and reliability--a price that in at least some cases may actually result in a general reduction of over-all system efficiency.

The emphasis placed by traditional biomechanics on the simple mechanical subsystems of man's body has not provided information that can be used readily by the engineer in designing effective control layouts. Competition for the favored control positions has become so severe that frequently the design engineer is faced with the problem of selecting arbitrarily a compromise position to be used.

It seems generally agreed that hand controls should be placed in front of the operator, somewhere between elbow and shoulder heights, and near the saggital plane of the active shoulder. This "ideal" area was determined primarily by the readiness with which controls in this area could be reached and manipulated, and also by the proximity of the control to the normal visual field-of-view--it was not determined by any reference to the forces that an operator could exert on controls in that area. In most of the studies in which several control locations have been evaluated only "favorable" positions were used (4 and 5). Thus at the present time there is very little information to aid a design engineer in selecting the optimal or acceptable locations for force-operated controls.

The working-space of the hand (or, rather, the maximum extension of the arm) has been plotted by others (1 and 6), but without reference to the amount of force that could be applied to controls within the area. Thus, for operations that require more than the application of slight

forces, these data may be of little use. That is to say, the limits of the "favorable" area will probably become more and more circumscribed as the force required to operate the control is increased.

A series of studies might be devoted to locating certain "force-spaces" within the work-space of the hand. For example, for each type of hand movement with a given type of control, areas might be located in which forces of 20-30 pounds, 30-40 pounds, 40-50 pounds, etc., could be applied. The data obtained from such studies should be sufficiently comprehensive that given a set of control requirements, the optimal and acceptable locations for the control could be determined; also, given the design-preferred control location, the control requirements could be stated.

The present study is meant to be the first in such a series. The over-all aim of the series of studies will be to measure the forces that can be applied within the work-space of the hand, and from this to determine the "force-spaces" of the hand for the more common movements. The specific object of this first study is to isolate the spatial factors influencing the force with which six linear hand movements can be made along the three orthogonal axes of an isometric control.

II. EXPERIMENTAL

Measurements were made of the maximum-exertable force that could be applied to a dynamometer handle by each of six linear hand movements (up, down, right, left, push, and pull). Five US Army enlisted men served as subjects. The maximum strength of each of the six movements was measured at five different handle distances (12 to 28 inches), four angular elevations (60° to 150°), and four lateral positions (0° to 90°) of the control. The center of the shoulder joint was used as the reference point for locating the control. Thus the direction of application of force was constant for all subjects regardless of size.

A. Apparatus

The apparatus employed in this study is shown in Figure 1. Basically, it consists of a dynamometer handle, a supporting structure for the handle, a bucket seat, and suitable strain-gauge amplifying and recording equipment.

The dynamometer handle is a modified copy of one designed by the Anthropology Section of the Aero Medical Laboratory, Wright-
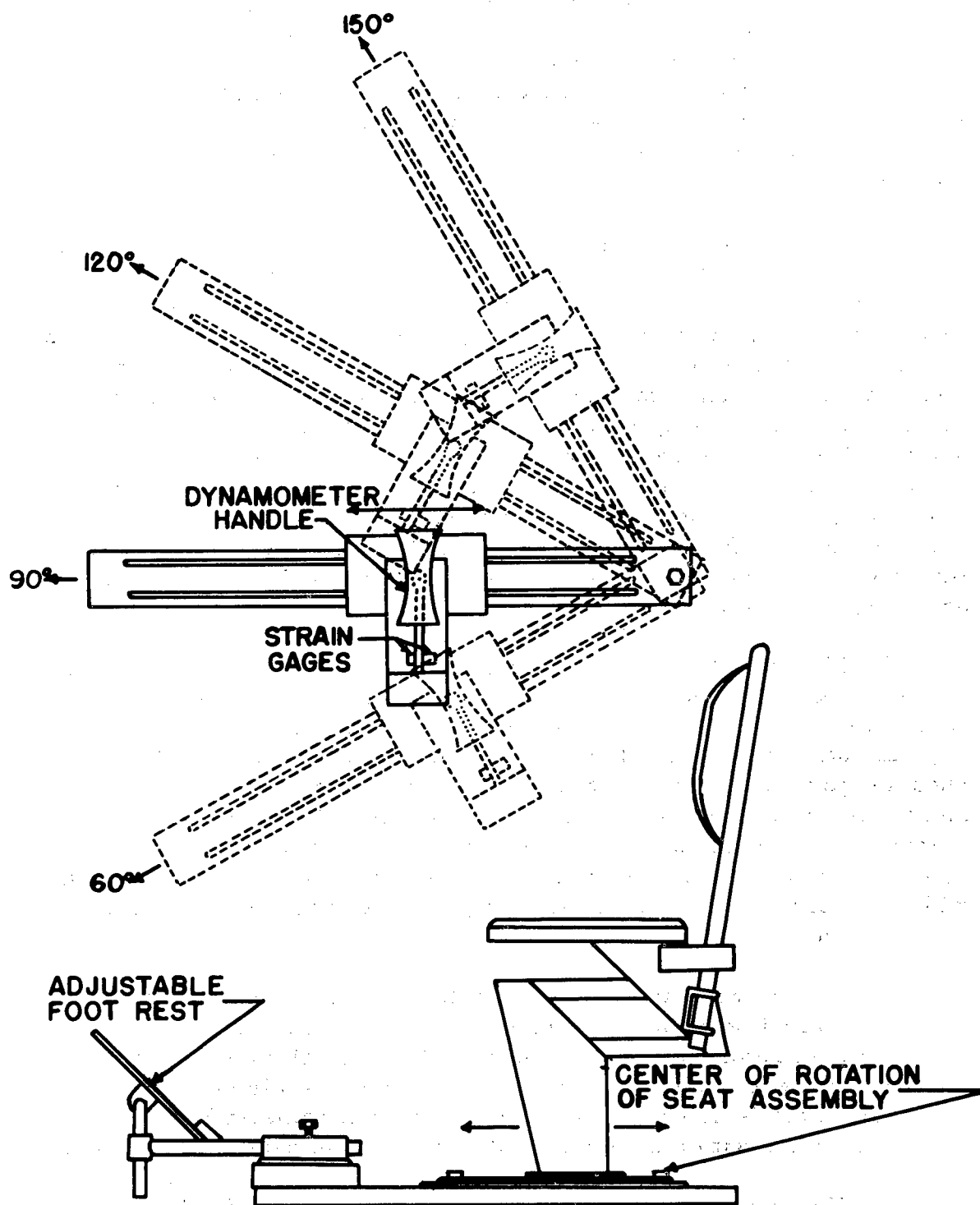
Fig. 1. Diagram of apparatus.

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Patterson Air Force Base, Ohio, for use with their Kinematic Muscle Study Machine (5). It is ball-mounted so that all subjects must grasp the handle identically regardless of hand size; i. e., all subjects must apply force to the center of the ball. If the handle is grasped too high (or too low), it will swivel when force is applied and immediately indicate to the operator and observer that the handle is being grasped incorrectly.

The handle is mounted on an L-shaped structure of 3/4-inch square tool steel. Three bridges of SR-4 strain gauges are also mounted on the bar in such a way as to be maximally sensitive to strain in the metal produced by forces applied along the three orthogonal axes of the handle. The handle mount is rigidly clamped when forces are applied along the $\underline{X}$ and $\underline{Z}$ axes to maximize strain in the region where the gauges are located. The clamp is loosened when forces are applied along the $\underline{Y}$ axis. The dynamometer handle is continuously adjustable along its support over a range of 16 inches to a maximum distance of 28 inches from the center of rotation. The supporting beam can be locked into four positions in the vertical plane: 60°, 90°, 120°, and 150°, where the 0° vertical reference line represents the normal position of the arm hanging loosely at the side.

The bucket seat used in this study was a scissors-type tank-driver's seat. It was modified to be adjustable as much as 5 inches in its $\underline{Z}$ axis, 2 inches in its $\underline{X}$ axis and 6 inches in its $\underline{Y}$ axis. These adjustments made it possible to set the center of rotation of the subject's shoulder joint directly over the center of rotation of the chair assembly and at the same height as the center of rotation of the handle mount. A plumb-bob was used to insure that this seating arrangement was used by all subjects. It was thus possible to position the subjects identically with respect to the handle, so that angular designations were identical for all subjects.

The entire seat assembly can be rotated and locked into four different lateral positions designated as 0°, 30°, 60°, and 90°; where the 0° lateral reference line represents the saggital plane of the shoulder. When the subject is thus rotated about the center of his shoulder joint, the same effect is produced as rotating the dynamometer handle in the horizontal plane with the subject's shoulder as the center of rotation.

The adjustments of the apparatus thus provide for independent positioning of the handle in the three orthogonal planes of space: (a) the handle can be set at distances between 12 and 28 inches from the shoulder joint, (b) the handle support can be rotated vertically to vary

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the handle's angular elevation, and (c) the seated subject can be rotated laterally to vary the lateral position of the control handle.

Each set of four strain-gauges mounted on the handle constitute a Wheatstone bridge. The outputs of the three bridges were amplified by Brush Strain Analyzers and then fed into Brush Direct-inking Oscillographs. Each system was calibrated, and conversion tables were constructed for use with the different directions of force; the applied forces could be measured with this apparatus within an error of ± 1 pound.

B. Subjects

Five US Army enlisted men were selected to serve as subjects in this study. They were selected primarily on the basis of availability. Three of them were approximately of average size, but the remaining two subjects represented the first and last decile of the US Army population. All subjects were in good health and good physical condition, and none evidenced any malfunction of the arm or hand used in this study.

C. Procedure

Five handle-distances (12, 16, 20, 24, and 28 inches) were combined factorially with four angular elevations (60°, 90°, 120°, and 150°) and with four lateral positions (0°, 30°, 60°, and 90°) in this study. Thus, there was a total of 80 distinct spatial control positions at which the subjects were tested. These positions are shown in Figure 2, page 6. The handle positions were presented in a random sequence with each subject receiving a different order of presentation. Each subject was tested once at each of these 80 positions with each of the six strength tests--i.e., push, pull, up, down, right, and left. The left-right movements were along the X axis of the handle, the up-down movements were along the Y axis, and the push-pull movements were along the handle's Z axis. It should be noted that the movements are defined with respect to the handle-shoulder axis rather than to gravity. This should lead to no misunderstanding if one will only remember that the terms "up" and "down" refer only to movements at right angles to a line connecting the handle and shoulder.

Prior to the experiment the subjects received practice at ten control positions other than the ones included in the actual testing. At this time the subjects were told to try to keep their
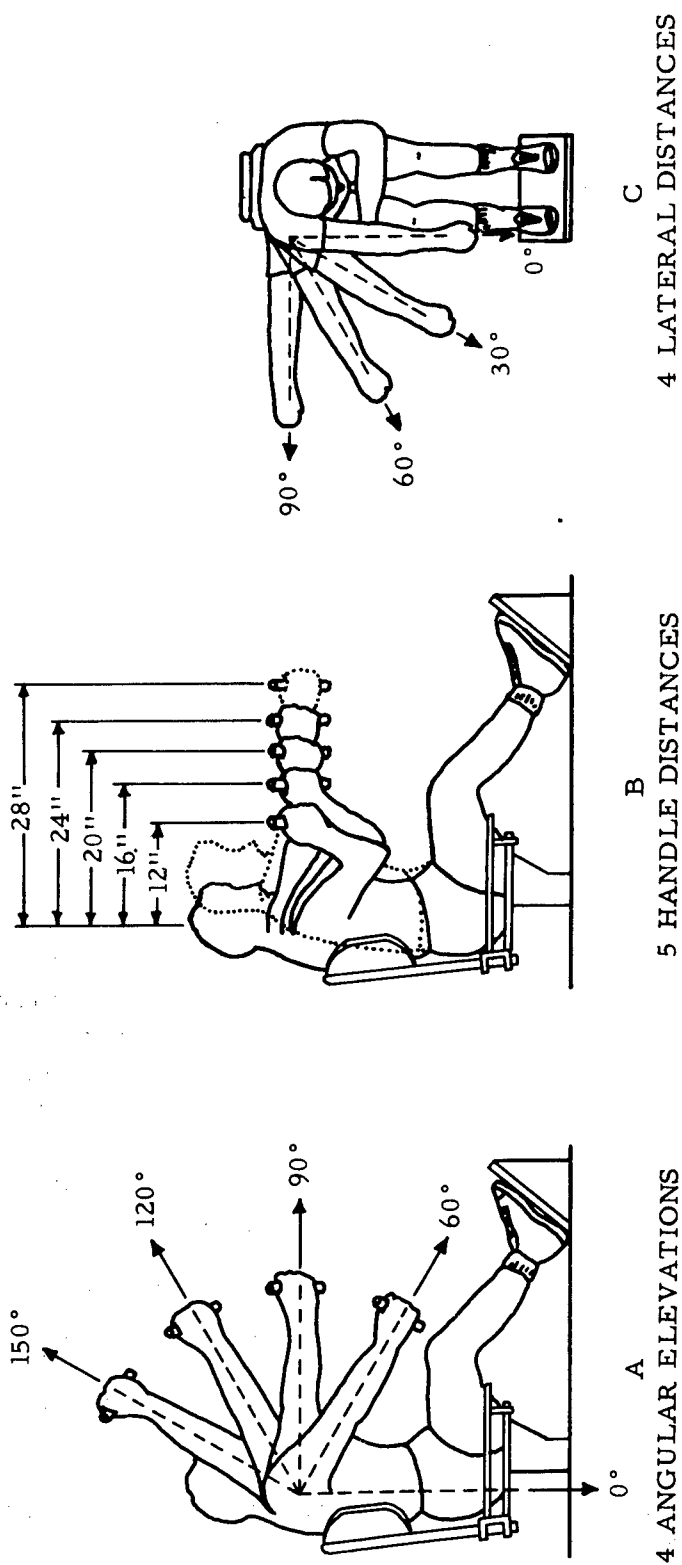
Fig. 2. The combination of four elevations, five distances, and four lateral positions of the control provided 80 positions at which the strengths of six movements were measured.

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elbows directly beneath the line connecting the shoulder and fist. Slight deviations from this position were ignored. There were very few instances in which it was necessary to discard trials because the elbow was placed in an extreme position, for apparently the prescribed position was the most natural one. The ten practice positions also made it possible to counterbalance the order of presentation of the six movements. Thus each movement appeared first in the sequence 15 times, second 15 times, etc. This was done to eliminate the possibility that the differences in the strengths of the movements might be due to practice or fatigue effects. Each subject was tested at five control positions per day for 16 days. The subject was told to exert as much force as possible in the designated direction. Each trial lasted 5 seconds and followed by a 55-second rest period before the subsequent trial was given. The subjects were informed that the maximum force exerted during the 5-second trial was all that would be recorded. All six strength tests (one trial for each direction of movement) were presented to a given subject at one of the 80 control positions before the next position was presented. There was a 5-minute rest period between successive positions.

Thus, an experimental session lasted approximately 45 minutes during which time the subject actually "worked" for only about 2.5 minutes. The timing of trials (test and rest periods) was based on recommendations made elsewhere by Hunsicker (5) who found that a similar schedule did not result in any appreciable fatigue.

III. RESULTS AND DISCUSSION

The data for each movement were analyzed by the method of orthogonal polynomials. This method provides much more information than the conventional analysis of variance because in addition to yielding F-ratios for the experimental variables and their interactions it also provides a means of testing the goodness of fit of regression lines of various degrees of complexity. In actual practice the sums of squares accounted for by the various regression lines are first determined and then the sums of squares for the main variables and the interactions are obtained by summating the components. Thus the use of this method in the present case enables one to test the effect of the lateral positions of the handle on the strength of a given movement, and then the data curve can be analyzed to determine which component of the curve--linear, quadratic, or cubic--is significant. The highest order curve which can be tested is one degree less than the number of data points. That is, if there are three points one can test the goodness of fit of a straight line and a quadratic curve; if there are four points one can test the fit of linear, quadratic

and cubic curves, and if there are five points one can test no higher than a quartic curve. This is evident from the orthogonal polynomials provided by Fisher and Yates (3).

The analyses of variances for the six movements are shown in Tables 1 and 2. Since a complete analysis is so lengthy, with 89 sources of variation for each movement, these tables are shortened to show all the sources of variation for the three main effects plus only the significant interactions. The residual is composed of all the subject interactions. This residual mean square provides the best measure of the uncontrolled variation among subjects treated alike, and thus would seem to be the most appropriate error term. The second-order interactions were tested against the residual mean square and none was found to be significant. Therefore, these interactions were combined with the residual error to form a pooled error term with 352 degrees of freedom. All the F-ratios for the main effects and simple interactions were obtained by dividing the mean squares by the mean square for the pooled error term.

TABLE 1

ANALYSIS OF VARIANCE OF THE FORCES EXERTED BY UP, DOWN, AND LEFT HAND MOVEMENTS

Source of Variation	df	UP SS	UP F	DOWN SS	DOWN F	LEFT SS	LEFT F
Lateral Angles (L)	3	321.18	2.31	7,599.94	19.14*	423.97	4.04*
Linear	1	183.62		2,677.30	20.22*	397.83	11.37*
Quadratic	1	121.00		4,515.84	34.12*	26.01	
Cubic	1	16.56		406.80		0.13	
Angular Elevations (E)	3	152.94	1.10	5,092.17	12.82*	4,034.27	38.42*
Linear	1	96.80		246.40		3,682.90	105.22*
Quadratic	1	44.89		4,329.64	32.71*	327.61	9.36*
Cubic	1	11.25		516.13		23.76	
Handle Distances (D)	4	5,715.41	30.82*	69,635.06	131.55*	9,944.93	71.03*
Linear	1	5,335.44	115.09*	69,080.44	521.95*	9,849.06	281.40*
Quadratic	1	370.30	7.99*	45.60		27.97	
Cubic	1	1.81		508.81		36.55	
Quartic	1	7.86		0.21		31.35	
Interaction: L x E	9	2,782.16	6.67*	2,466.49	2.07	2,076.06	6.59*
Linear x Linear	1	1,836.98	39.62*			1,622.48	46.36*
Quadratic x Linear	1						
Interaction: L x D	12	624.71	1.12	2,142.09	1.34	528.29	1.25
Linear x Linear							
Interaction: E x D	12	496.32	0.59	8,675.47	5.46*	366.09	0.87
Linear x Linear	1			4,000.00	30.22*		
Linear x Quadratic	1			1,368.18	10.33*		
Quadratic x Linear	1			1,485.12	11.22*		
Interaction: L x E x D	36	1,736.67	1.04	4,340.56	0.90	972.05	0.75
Between Subjects	4	8,793.50	47.42*	52,977.76	100.10*	7,666.83	54.76*
Residual	316	14,584.10	46.15	42,248.02	133.70	11,347.17	35.91
Total	399	35,207.00		195,197.56		37,359.67	
MS Pooled Error (Residual + L x E x D)	352	46.36		132.35		35.00	

*Significant at 1% level of confidence

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TABLE 2

ANALYSIS OF VARIANCE OF THE FORCES EXERTED BY RIGHT, PUSH, AND PULL HAND MOVEMENTS

Source of Variation	df	RIGHT		PUSH		PULL	
		SS	F	SS	F	SS	F
Lateral Angles (L)	3	922.40	27.19*	20,882.90	7.21*	404.62	0.92
Linear	1	850.21	75.17*	11,775.80	12.19*	292.61	
Quadratic	1	64.00		8,826.60	9.14*	109.20	
Cubic	1	8.19		280.50		2.81	
Angular Elevations (E)	3	42.02	1.25	15,745.00	5.43*	7,871.80	17.82*
Linear	1	32.26		79.60		548.10	
Quadratic	1	8.41		11,848.32	12.27*	7,318.80	49.71*
Cubic	1	1.35		3,817.08		4.90	
Handle Distances (D)	4	2,402.01	53.09*	274,637.65	71.10*	22,605.02	38.38*
Linear	1	2,363.28	208.95*	200,154.64	207.26*	22,123.56	150.26*
Quadratic	1	26.11		50,518.29	52.31*	107.51	
Cubic	1	7.03		17,512.56	18.13*	21.45	
Quartic	1	5.59		6,452.16		352.50	
Interaction: L x E	9	300.27	2.95*	28,164.71	3.24*	4,587.68	3.46*
Linear x Linear	1			19,743.06	20.44*	4,013.22	27.26*
Quadratic x Linear	1	112.34	9.93*				
Interaction: L x D	12	286.42	2.11	26,072.76	2.25*	1,773.92	1.00
Linear x Linear	1	121.45	10.74*	12,166.14	12.60*		
Interaction: E x D	12	195.69	1.44	35,690.47	3.08*	6,863.16	3.88*
Linear x Linear	1	105.30	9.31*	17,322.24	17.94*	3,753.91	25.49*
Linear x Quadratic	1						
Quadratic x Linear	1						
Interaction: L x E x D	36	281.94	0.67	18,528.81	0.51	5,287.05	1.00
Between Subjects	4	4,059.04	89.72*	16,315.26	4.22*	7,087.00	12.03*
Residual	316	3,697.76	11.70	321,401.54	1017.09	46,541.00	147.28
Total	399	12,187.55		757,439.10		103,021.25	
MS Pooled Error (Residual + L x E x D)	352	11.31		965.71		147.24	

*Significant at 1% level of confidence

In order that the reader might better understand the table contents and at the same time obtain an appreciation of the uses of the method of orthogonal polynomials the method is outlined in the Appendix and a few sample problems from the analysis are presented. This is considered appropriate because very little use has been made of this method by psychologists, and in the instances when it can be used this form of analysis is far more descriptive than the more commonly used techniques. This method is most easily applied in those cases in which there are equal intervals between the various values of the independent variable, and the same number of observations are made at each value.

In the Appendix are six figures showing the estimated strength of each movement at each of the 80 control positions. (These estimates were obtained from equations derived by the method of orthogonal polynomials.) In these semischematic figures the control positions are indicated by the dots at the intersections of the dashed distance arcs with the four lines converging on the shoulder which indicate the four angular elevations. Since these values are estimates derived from the

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performance of only five subjects they should not be assumed to be stable norms. However, these values--and the formulae from which they were derived--may be used to determine the relative merits of various control positions for the six movements. In each figure are shown four or five curves. Each curve connects points in the working area at which equal strength of movement is predicted from the formula. From these arbitrarily chosen "isodynes" one can assess the relative effects of the distance, angular elevation, and lateral position of the handle on the strength of movement.

The results for the six movements will now be considered. Since the effects of the experimental variables differed so greatly for the various movements the results must be discussed separately. There was only one factor common to all movements: namely, a highly significant F-ratio for "Between Subjects." This merely reflects the differences among the subjects in absolute strength. In general, the strongest subject had about twice the output of the weakest subject.

A. The Up Movement

The mean strength of the up movement at the various control locations is shown in Tables 3, 4, and 5. It is apparent from the analysis of variance outlined in Table 1 that neither the lateral position of

TABLE 3

FORCE OF THE SIX CONTROL MOVEMENTS AT THE FOUR LATERAL POSITIONS
FOR THE FOUR ANGULAR ELEVATIONS OF THE HANDLE

Vertical Position	Lateral Position of Handle									
	UP					DOWN				
	$0°$	$30°$	$60°$	$90°$	Mean	$0°$	$30°$	$60°$	$90°$	Mean
$60°$	36.4	29.0	28.8	23.5	29.4	55.1	58.0	55.6	51.4	55.0
$90°$	29.8	27.5	28.2	26.5	28.0	67.2	70.5	59.6	53.9	62.8
$120°$	24.7	28.9	29.9	28.6	28.0	57.2	66.1	60.7	52.3	59.1
$150°$	24.3	30.3	28.6	28.6	28.0	49.7	60.0	58.1	47.5	53.8
Mean	28.8	28.9	28.9	26.8	28.4	57.3	63.6	58.5	51.3	57.7
	LEFT					RIGHT				
	$0°$	$30°$	$60°$	$90°$	Mean	$0°$	$30°$	$60°$	$90°$	Mean
$60°$	44.0	37.8	35.3	32.1	37.3	25.5	20.2	20.3	19.9	21.5
$90°$	33.1	33.5	31.4	31.4	32.4	23.7	21.8	19.0	19.6	21.0
$120°$	30.2	31.8	30.0	29.2	30.3	22.6	21.6	19.9	18.4	20.6
$150°$	25.9	28.7	31.4	29.9	29.0	21.7	20.5	21.2	19.6	20.7
Mean	33.3	33.0	32.0	30.6	32.2	23.4	21.0	20.1	19.4	21.0
	PUSH					PULL				
	$0°$	$30°$	$60°$	$90°$	Mean	$0°$	$30°$	$60°$	$90°$	Mean
$60°$	120.0	116.0	87.9	73.8	99.4	94.7	89.4	86.8	80.8	87.9
$90°$	103.5	113.7	105.1	95.4	104.4	82.2	80.2	76.8	73.3	78.1
$120°$	107.0	119.1	117.9	105.2	112.3	73.2	77.8	79.1	79.4	77.4
$150°$	90.0	95.8	105.4	90.8	95.5	80.3	84.8	85.6	88.0	84.7
Mean	105.1	111.2	104.1	91.3	102.9	82.6	83.0	82.1	80.4	82.0

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TABLE 4

FORCE OF THE SIX CONTROL MOVEMENTS AT THE FOUR ANGULAR ELEVATIONS FOR THE FIVE HANDLE DISTANCES

Handle Distance — Angular Elevation of Handle

Handle Distance	UP					DOWN				
	60°	90°	120°	150°	Mean	60°	90°	120°	150°	Mean
12"	35.0	35.6	34.8	33.2	34.7	61.6	80.8	81.6	79.4	75.8
16"	34.2	29.9	28.8	28.6	30.4	60.1	78.8	70.7	63.9	68.4
20"	28.0	27.1	26.8	26.0	27.0	59.0	63.4	56.7	49.8	57.2
24"	26.2	23.6	25.2	26.7	25.5	50.4	50.1	43.6	42.8	46.7
28"	23.6	23.9	24.3	25.2	24.2	44.1	41.0	42.8	33.2	40.3
Mean	29.4	28.0	28.0	28.0	28.4	55.0	62.8	59.1	53.8	57.7

Handle Distance	LEFT					RIGHT				
	60°	90°	120°	150°	Mean	60°	90°	120°	150°	Mean
12"	43.9	40.2	36.6	36.3	39.2	24.0	25.2	24.4	25.5	24.8
16"	40.2	33.6	33.8	33.1	35.2	22.1	22.0	22.4	23.4	22.5
20"	40.4	33.1	29.5	29.1	33.0	21.8	20.4	20.0	19.6	20.5
24"	33.2	29.4	27.9	25.6	29.0	20.8	20.0	18.4	18.6	19.4
28"	29.0	25.6	23.7	20.8	24.8	18.8	17.6	18.0	16.6	17.7
Mean	37.3	32.4	30.3	29.0	32.2	21.5	21.0	20.6	20.7	21.0

Handle Distance	PUSH					PULL				
	60°	90°	120°	150°	Mean	60°	90°	120°	150°	Mean
12"	70.8	69.4	62.6	51.6	63.6	67.4	67.3	69.6	79.6	71.0
16"	82.9	87.6	85.1	65.0	80.1	78.2	72.3	74.0	81.1	76.4
20"	122.5	130.4	139.8	98.4	122.8	95.2	79.3	78.8	83.2	84.1
24"	112.1	129.8	138.8	141.2	130.5	91.7	87.4	78.9	87.0	86.2
28"	108.9	104.8	135.2	121.2	117.5	107.0	84.2	85.5	92.6	92.3
Mean	99.4	104.4	112.3	95.5	102.9	87.9	78.1	77.4	84.7	82.0

TABLE 5

FORCE OF THE SIX CONTROL MOVEMENTS AT THE FOUR LATERAL POSITIONS FOR THE FIVE HANDLE DISTANCES

Handle Distance — Lateral Position of Handle

Handle Distance	UP					DOWN				
	0°	30°	60°	90°	Mean	0°	30°	60°	90°	Mean
12"	36.2	35.2	34.2	33.1	34.7	77.2	86.4	77.8	61.9	75.8
16"	29.4	29.6	31.1	31.6	30.4	67.2	74.2	69.2	63.0	68.4
20"	26.1	28.2	28.4	25.2	27.0	55.8	61.4	58.4	53.2	57.2
24"	24.8	27.4	26.1	23.6	25.5	45.5	52.2	47.1	42.1	46.7
28"	27.4	24.3	24.6	20.6	24.2	40.8	43.9	40.2	36.2	40.3
Mean	28.8	28.9	28.9	26.8	28.4	57.3	63.6	58.5	51.3	57.7

Handle Distance	LEFT					RIGHT				
	0°	30°	60°	90°	Mean	0°	30°	60°	90°	Mean
12"	40.6	40.6	37.1	38.6	39.2	28.4	24.8	23.8	22.0	24.8
16"	38.4	35.3	34.8	32.2	35.2	25.8	21.2	21.7	21.2	22.5
20"	34.6	33.0	34.2	30.2	33.0	23.8	21.0	19.0	18.1	20.5
24"	27.4	30.8	29.4	28.5	29.0	20.0	20.1	19.0	18.6	19.4
28"	25.6	25.1	24.6	23.7	24.7	18.9	18.0	17.1	16.9	17.7
Mean	33.3	33.0	32.0	30.6	32.2	23.4	21.0	20.1	19.4	21.0

Handle Distance	PUSH					PULL				
	0°	30°	60°	90°	Mean	0°	30°	60°	90°	Mean
12"	64.1	66.7	61.8	61.8	63.6	70.2	72.2	73.3	68.1	71.0
16"	74.8	77.9	86.2	81.6	80.1	73.7	76.8	76.6	78.4	76.4
20"	118.6	142.8	124.4	105.2	122.8	82.4	86.1	85.1	83.0	84.1
24"	129.8	143.6	135.7	113.0	130.5	89.8	88.1	85.9	81.2	86.2
28"	138.2	124.8	112.2	94.8	117.5	96.8	91.8	89.4	91.2	92.3
Mean	105.1	111.2	104.1	91.3	102.9	82.6	83.0	82.1	80.4	82.0

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the handle nor its angular elevation, when taken singly, had a statistically significant influence on the force of this movement. It is shown in Table 3 that the mean strength of movement was the same at the 0°, 30°, and 60° lateral position and that it dropped slightly at the 90° position. There was a difference of only 2.1 pounds between the means at the best and poorest lateral positions. It is shown, too, that the mean output was the same at the 90°, 120°, and 150° elevations and that the output at the most favorable elevation (60°) was only 1.4 pounds greater than at the other elevations.

Table 1 shows that there was a statistically significant inter-action between "Lateral Angles" and "Angular Elevations." Thus it may be stated that the optimum elevation of the handle was dependent upon its lateral position. As seen in Figure 3 the most favorable position of the handle for this movement was at the 0° lateral position, or in front of the shoulder, and at the lowest (60°) elevation. When the handle was at the 30° and 60° lateral positions there was little difference in the mean forces obtained at the different elevations, but when the control was located at the side the high positions (120° or 150°) were most favorable. In general, it may be said that the low frontal position of the handle is best and that as the handle is positioned more toward the side its elevation should be increased. The fact that this was a linear x linear interaction indicates that the trends of the means for each angular elevation if approximated by a straight line would have slopes that would be different by constant amounts for the various lateral positions of the handle.

There was a statistically significant difference in the per-formances at the various handle distances. In Figure 4 and Table 4 it is shown that the 12-inch handle distance was best and that as the distance was increased there was an abrupt and progressive decrease in the force of the movement. This curve had statistically significant linear and quadratic components. Thus a straight line accounted for a significant amount of the variance but when this variance was removed a quadratic curve accounted for a significant amount of the variance in the remainder. The force of the movement at the 28-inch distance was 30%, or 10.4 pounds less than at the 12-inch position. As indicated by the significant quad-ratic component, the rate of decrease of output diminished as the handle distance increased.

B. The Down Movement

Table 1 shows that there was a statistically significant dif-ference in the force of the down movement at the various lateral positions

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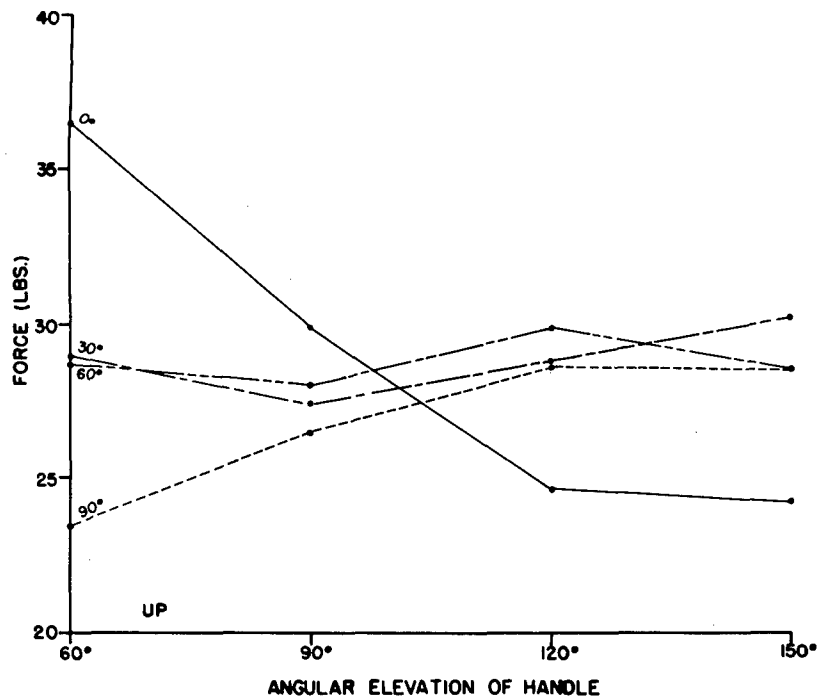
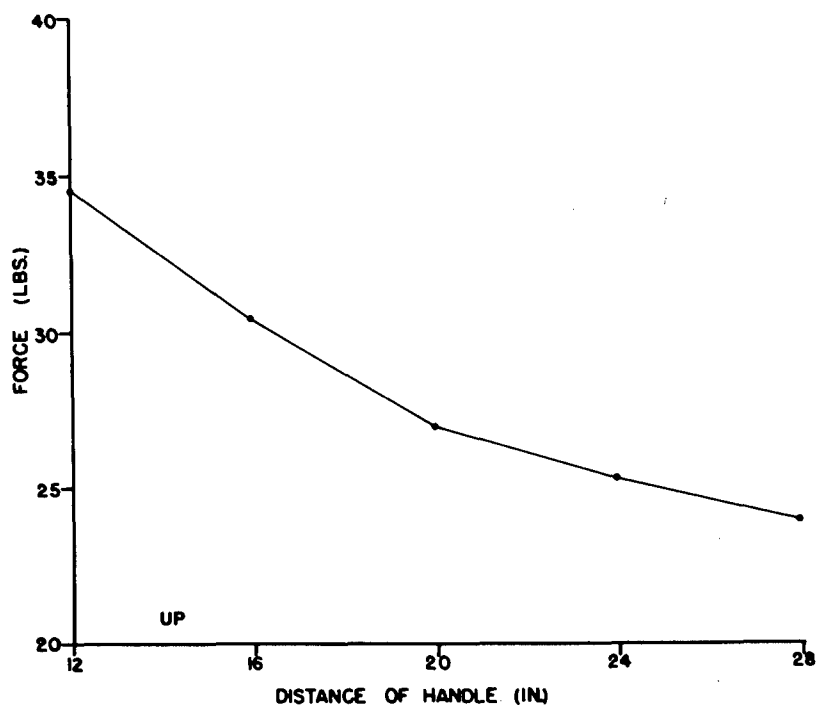Fig. 3. Force of up movement at four angular elevations for the four lateral positions of the handle.

Fig. 4. Force of up movement at the five handle distances.

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of the handle. The curve shown in Figure 5 was found to have sig-
nificant linear and quadratic components. The output increased as the
handle was moved from the 0° to the 30° lateral position and then de-
creased progressively as the handle was moved farther toward the side.
The movement was strongest at the 30° lateral position and weakest at
90°. From Table 3 it may be seen that there was a 12.4 pounds dif-
ference in mean strength at these two positions. Thus, despite the fact
that there was a statistically significant difference among the lateral
positions, the output at the poorest position was only 20% less than at
the best position. There was no essential difference in the means for
the 0° and 60° lateral positions.

An examination of Table 1 shows that there was a statistically
significant difference between the effects of the various angular
elevations of the handle on the strength of the down movement. It
may be seen, too, that the curve shown in Figure 6 had a statistic-
ally significant quadratic component. This figure and Table 3 reveal
that mean strength increased as the handle elevation was increased
from 60° to 90° and that it then decreased as the handle elevation
was further increased. There was a difference of only 9 pounds be-
tween the means for the best (90°) and poorest (150°) elevations.
That is, the mean output at the least favorable elevation was only
14% less than at the best elevation.

The handle distance had a much greater effect on the strength
of the movement than did either of the other main variables. It may
be seen in Table 4 and Figure 7, page 16, that the down movement
was strongest at the 12-inch handle distance and that the strength de-
creased rapidly as the distance was increased. The analysis of vari-
ance demonstrates that only a straight line fit to the data removed
a significant amount of the variance. The mean force of movement
dropped at a steady rate from 75.8 pounds at the 12-inch handle
distance to 40.3 pounds at the 28-inch. Thus at the farthest position
of the control the output was only 53% of that at the 12-inch position.
It may be seen from the portion of the formula for the handle distance
alone, -9.28 $(\frac{D-20}{4})$, that for each inch increase in distance there was
a mean reduction in output of 2.32 pounds. However, since there was
a statistically significant interaction between "Angular Elevations"
and "Handle Distances" the effect of handle distance cannot be in-
terpreted without taking the elevation of the handle into consideration.
At every elevation the strength of the movement decreased as the
handle distance was increased but the amount of the decrease was
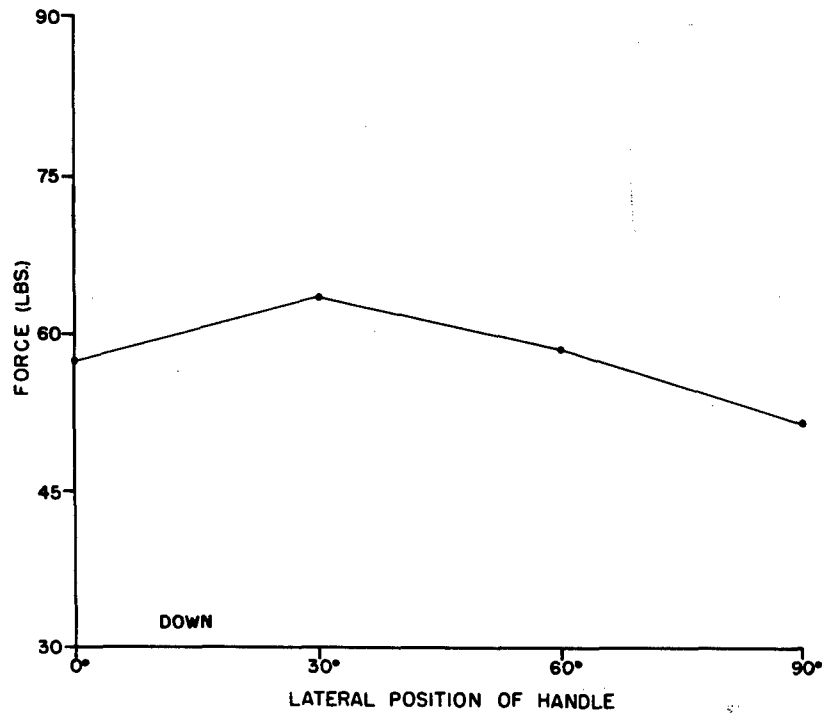dependent upon the angular elevation of the handle. It is shown in

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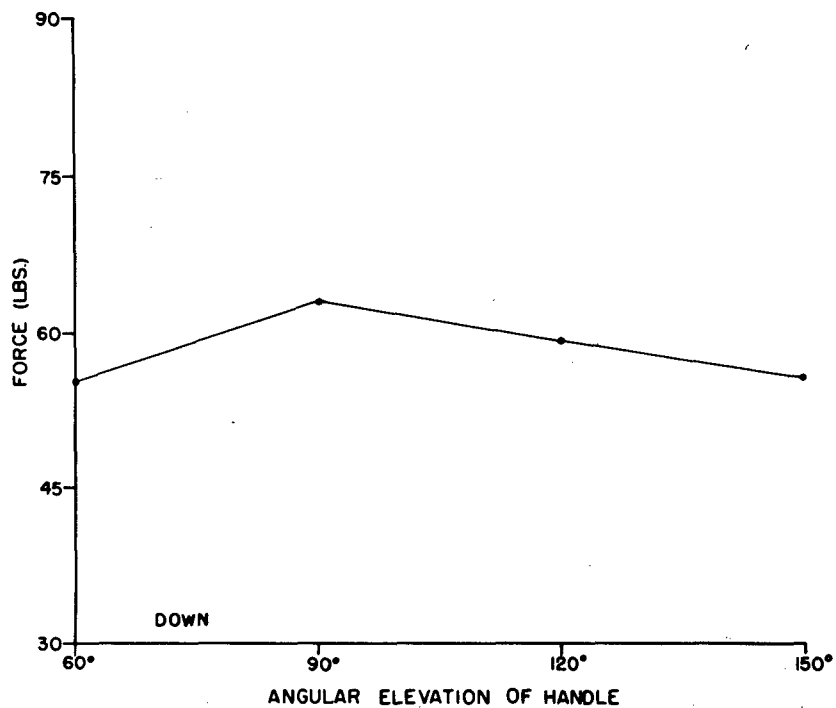Fig. 5. Force of down movement at four lateral positions of the handle.

Fig. 6. Force of down movement at four angular elevations of the handle.

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Figure 7 that handle distance had much less effect at the 60° elevation
than at the others. Table 4 shows that the differences between the forces
measured at the 12-inch and 28-inch distances at the four angular ele-
vations are as follows: 17.5 pounds at 60°, 39.8 pounds at 90°, 38.8
pounds at 120°, and 46.2 pounds at 150°. Thus the effect of distance
on the strength of the down movement was about two and one-half times
greater at 150° than at 60°. The curve for the 60° elevation reveals
one interesting and unexpected feature: namely, that there were no
appreciable differences in the performances at the 12-inch, 16-inch,
and 20-inch distances, while at the 120° and 150° elevations this was
a region of maximum effect. In general, the distance effect increased
with handle elevation.
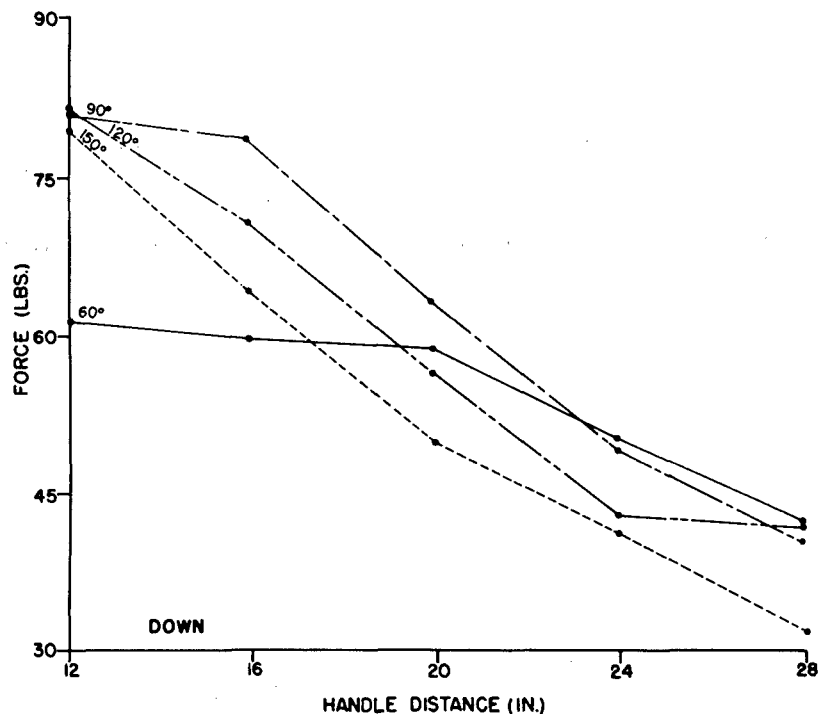
Fig. 7. Force of down movement at five distances for the four angu-
lar elevations of the handle.

C. The Left Movement

There was a statistically significant difference between the
outputs measured at the various lateral positions of the control. The
analysis of variance shown in Table 1 indicates that a straight line best
approximated the means. In Table 5 one can see that this movement

was strongest when the control was in front of the shoulder, or at the 0° lateral position, and that the force of movement decreased slightly though progressively as the handle was moved laterally. The difference in the mean forces of the responses at the 0° and 90° lateral positions was only 2.7 pounds so it may be stated that the lateral position of the handle _per se_ was of no practical significance. As we shall see later, the effect of the lateral position of the handle on the output was greatly dependent upon the angular elevation of the handle.

The angular elevation of the handle also had a statistically significant effect on the strength of this movement. The analysis of variance shows that the curve fitting the means for the four elevations had significant linear and quadratic components. A straight line accounted for much more of the variance than did a quadratic curve. As shown in Table 3 the movement was strongest at the 60° elevation and it decreased progressively to a minimum at 150°. The curve fitting the means is negatively accelerated; that is, the rate of loss of strength decreased as the elevation increased. There was a difference of 8.3 pounds between the means for the lowest and highest elevations. It should be kept in mind, however, that since there was a significant interaction between "Lateral Positions" and "Angular Elevations" the elevation effect was not the same at all lateral positions of the handle.

This "Lateral Angles" by "Angular Elevations" interaction is shown in Figure 8. It is obvious here that if the results for the four
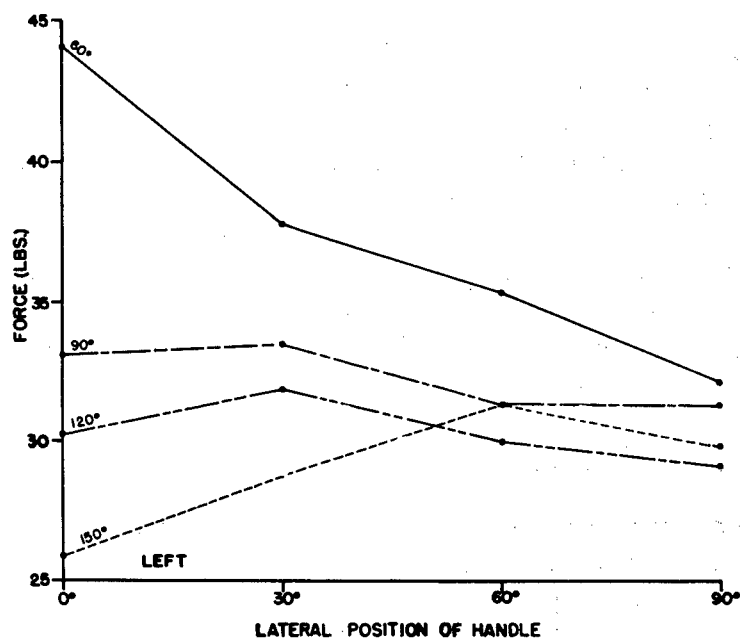
Fig. 8. Force of left movement at four angular elevations for four lateral positions of handle.

elevations are combined there would be little difference among the means for the various lateral positions. Also, it is apparent that at all lateral positions the output was greatest when the handle was at the 60° angular elevation and that the 90° elevation was superior to the 120° elevation at all lateral positions. The 150° elevation was markedly inferior to the others when the control was at the 0° and 30° lateral positions but when the handle was at the side the output at 150° elevation was slightly greater than at the 90° and 120° elevations. At the 60° elevation the strength of movement decreased progressively as the handle was moved farther toward the side. The output at the 90° lateral position was 12.9 pounds, or approximately 35% less than at the 0° position. At the 90° and 120° elevations the lateral position of the handle had little influence on the strength of movement. At these elevations there was less than three pounds difference between the outputs at the best (30°) and poorest (90°) lateral positions. At the highest elevation the results were the opposite of those obtained at the 60° elevation: that is, output was least when the control was in front of the shoulder and it increased as the control was positioned more and more toward the side. The difference between the mean strengths at the best and poorest elevations decreased from a maximum of 18.1 pounds at the 0° lateral position to a minimum of 2.9 pounds at the 90° lateral position. This interaction between elevations and lateral angles was found to be linear x linear so it may be stated that the curves for the various elevations shown in Figure 4 are essentially linear in form.

It is shown in Table 1 that the strength of movement was greatly dependent upon the handle distance, and that a linear fit to the five means accounted for practically all of the variance contributed by "Handle Distances." From Figure 9 and Table 3 it may be seen that the movement was strongest at the 12-inch distance and that output decreased steadily as the handle distance increased. Mean strength at the 28-inch distance was 14.4 pounds or 37% less than at 12 inches. A comparison of Figure 9 with Figure 8 reveals that the handle distances had a much greater effect on response strength than did either the lateral angles or the angular elevations considered separately.

D. The Right Movement

As shown in the analysis of variance outlined in Table 2 there was a statistically significant difference in the mean strengths of response at the four lateral positions of the handle. It is shown, too, that a straight line provided the closest fit to the data points. The data are presented in Table 3 where it may be seen that the output was greatest
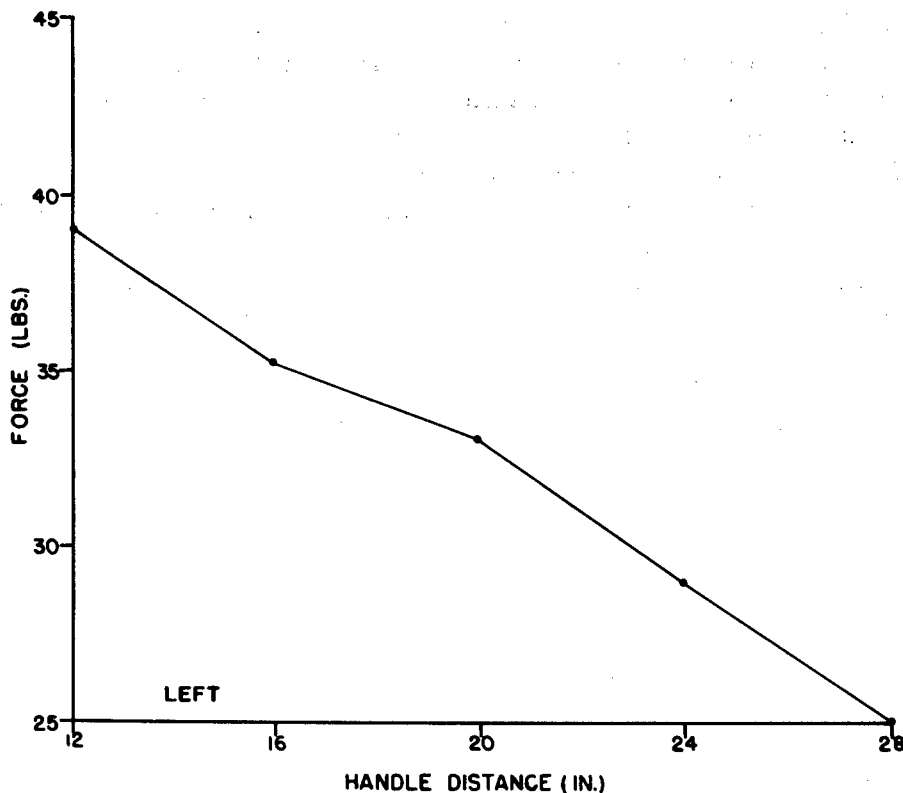
18

Fig. 9. Force of left movement at five handle distances.

when the handle was in front of the shoulder and least at the most lateral
handle positions. There was a difference of only 4.0 pounds between the
means at the 0° and 90° lateral positions. Now when interpreting the
effect of the lateral position of the handle on the output of the subjects
one must take into consideration the fact that "Lateral Angles" interacted
significantly with both "Angular Elevations" and "Handle Distances." In
Figure 10, page 20, it may be seen that the lateral positions of the handle
had a somewhat different effect at the four elevations. The analysis of
variance indicated that this was a quadratic by linear interaction; that is,
the data for the 60° handle elevation at the four lateral positions were
approximated best by a quadratic curve but as the handle elevation was
progressively increased the quadratic component decreased and the
linear component became increasingly stronger. From the curve for
the 60° elevation it is apparent that when the handle was moved from the
0° to the 30° lateral position there was an abrupt decrease in output but
the output was not further reduced as the handle was moved more toward
the side. At the 90° elevation the output progressively decreased as the
handle was moved from the 0° to the 60° lateral position and then it

increased slightly at the 90° lateral position. The data for the 120° and 150° elevations can be fairly well approximated by straight lines. At all elevations the frontal (0°) position of the handle was best, but the degree of superiority of this lateral position over the others was progressively reduced as the handle was raised. The differences in the mean forces at the best and poorest lateral positions decreased from 5.6 pounds at 60° angular elevation to 2.1 pounds at the 150° elevation. Except at the 0° lateral position, there were small differences among the forces measured at the various angular elevations.
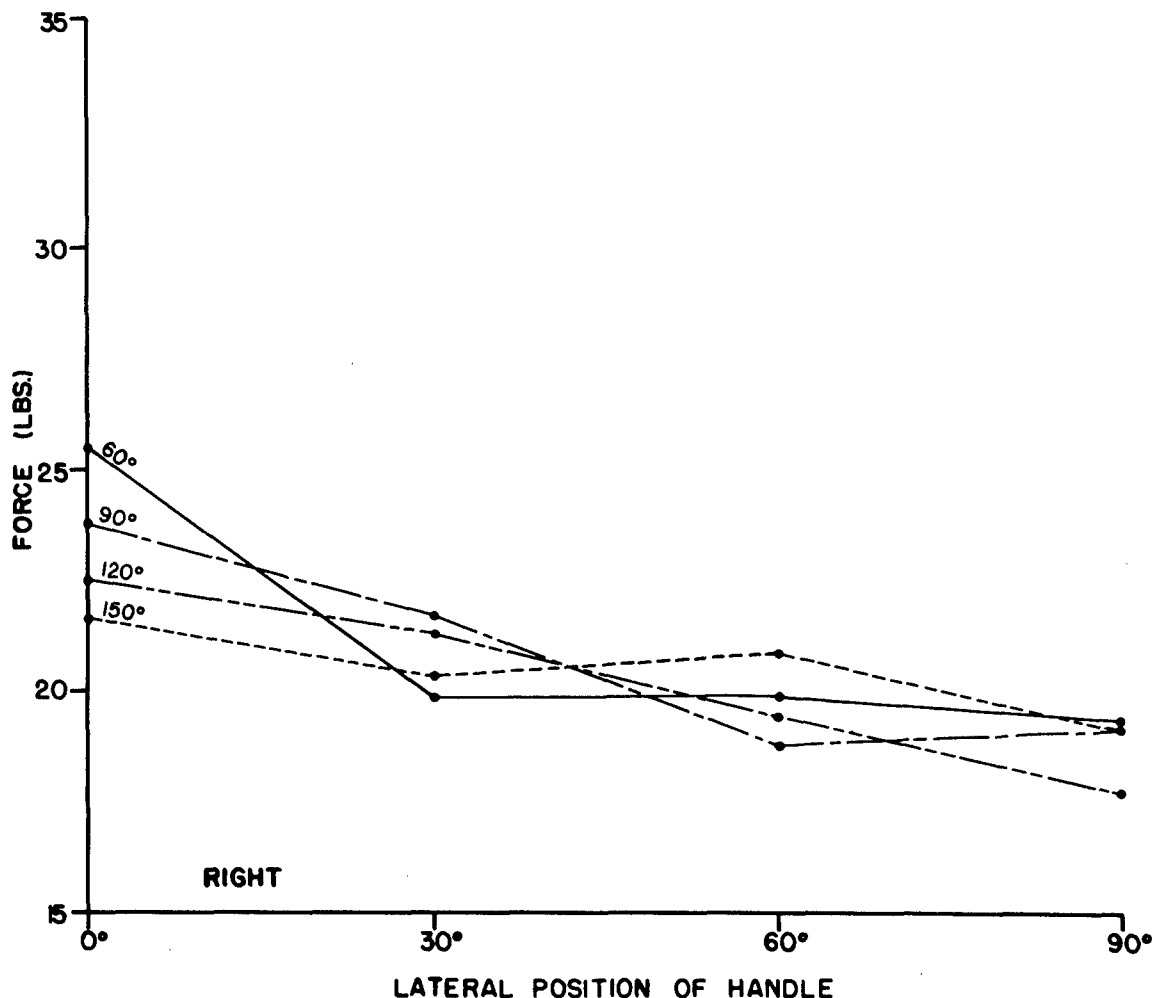
Fig. 10. Force of right movement at four lateral positions for four angular elevations of handle.

It is shown in Table 2 that there was a statistically significant linear x linear interaction between "Lateral Angles" and "Handle Distances." The handle distance had a significant effect upon the strength

of movement.   The analysis of variance indicates that a straight line
provided the best fit for the five means for the handle distance.   It is
shown in Figure 11 and Table 5 that this movement was strongest at the
12-inch handle distance and that the output decreased as the handle
distance increased.   The force of the movement decreased from 24.8
pounds at the 12-inch distance to 17.7 pounds at 28 inches.   Thus the
output of the subjects at the 28-inch handle distance was approximately
28% less than at 12 inches.   The extent of the influence of the handle
distance on the output of the subjects was dependent upon the lateral
position of the handle.   The handle distance had its greatest effect
when the control was placed in the mid-line of the shoulder and least
effect when the handle was directly at the side.   When the handle was at
the 0° lateral position there was a 9.5 pounds difference between the
output at the 12-inch and 28-inch distances, and when it was at the 90°
lateral position this difference decreased to 5.1 pounds.   Since this is
a linear by linear interaction it may be stated that the data for the handle
distances were approximated best by a straight line and that the slope
of the line decreased as the handle was moved farther and farther toward
the side.
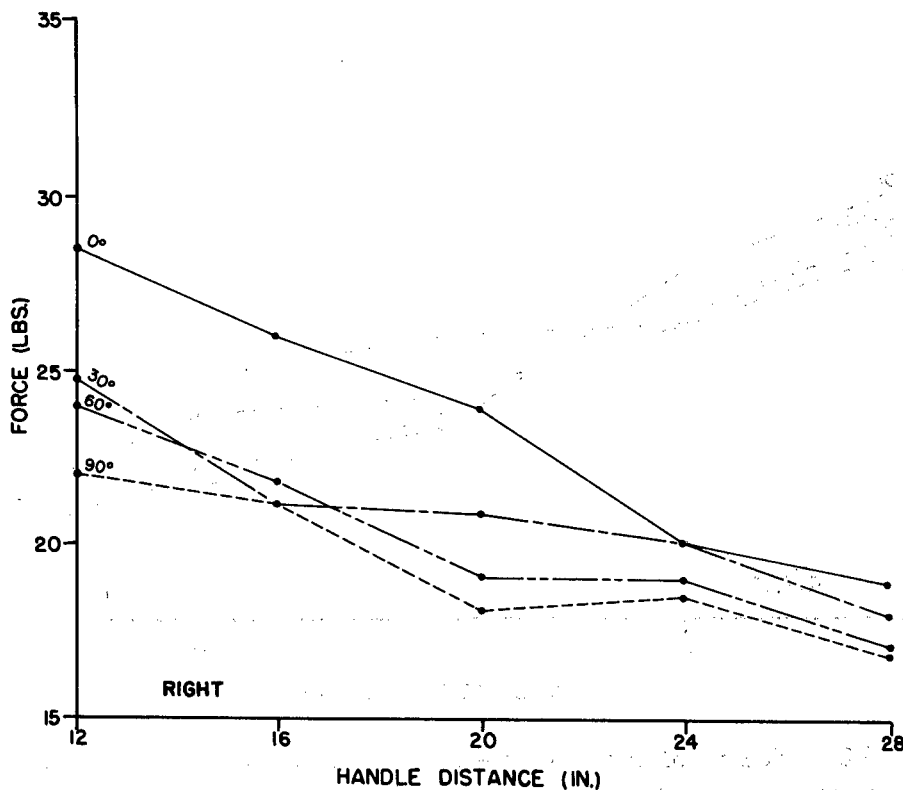
Fig. 11.   Force of right movement at five distances for the
four lateral positions of the handle.

A slight though statistically significant interaction was found between "Angular Elevations" and "Handle Distances." The analysis of variance showed that the data for the various handle distance at each elevation were approximated best by a straight line and that the slope of the line changed as a function of the elevation. In Figure 12 and Table 4 it may be seen that the effect of handle distance on the output increased with the elevation of the handle. At 60° elevation the difference between the mean forces measured at the 12-inch and 28-inch distances was 5.2 pounds and at 150° elevation the difference increased to 8.9 pounds. It may be seen here, too, that at the near positions of the handle the high elevation tended to be best, while at the far handle positions the lowest elevation was best.
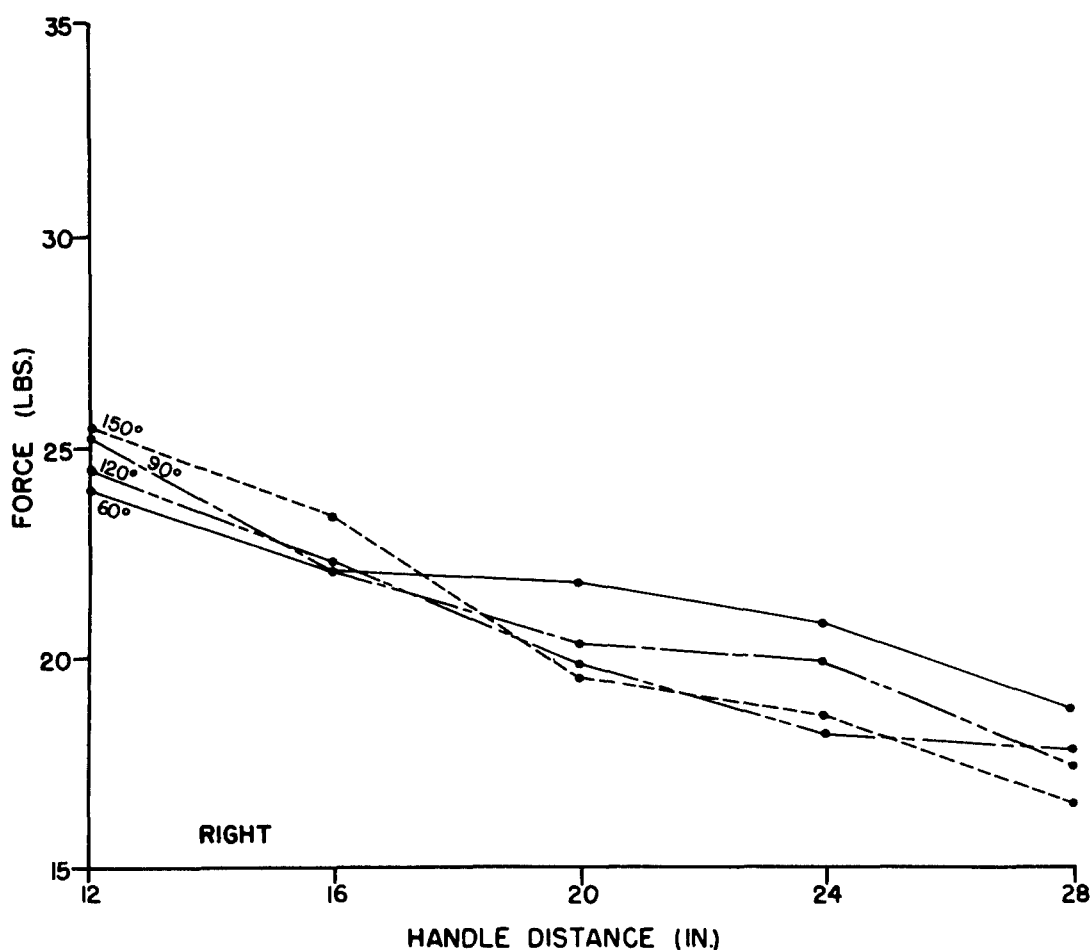
Fig. 12. Force of right movement at five distances for the four angular elevations of the handle.

E.   The Push Movement

In Table 2 it is shown that the F-ratio for "Lateral Positions" was significant at the 1% level of confidence and that the curve fitting the means had statistically significant linear and quadratic components. From Figure 13 it should be obvious, however, that the effect was slight.   An examination of Table 3 reveals that the output was greatest at the 30° lateral position and least at the 90° position.   In Figure 13 it is apparent that there was little difference in the performances at the 0°, 30°, and 60° positions and that the force of movement was appreciably decreased only when the handle was located at the side. From the analysis of variance and Figure 13 one may see that the effect of the lateral position of the handle on the strength of movement was not the same at all handle elevations.   Since only the linear by linear inter-action was significant it may be said that at any lateral angle the means for the four angular elevations were most closely approximated by a straight line and that the slope of this line was different at the various lateral angles.   At the 0° and 30° lateral angles the low positions of the handle tended to be best while at the 60° and 90° lateral angles the high positions, particularly the 120° elevation, were to be preferred.
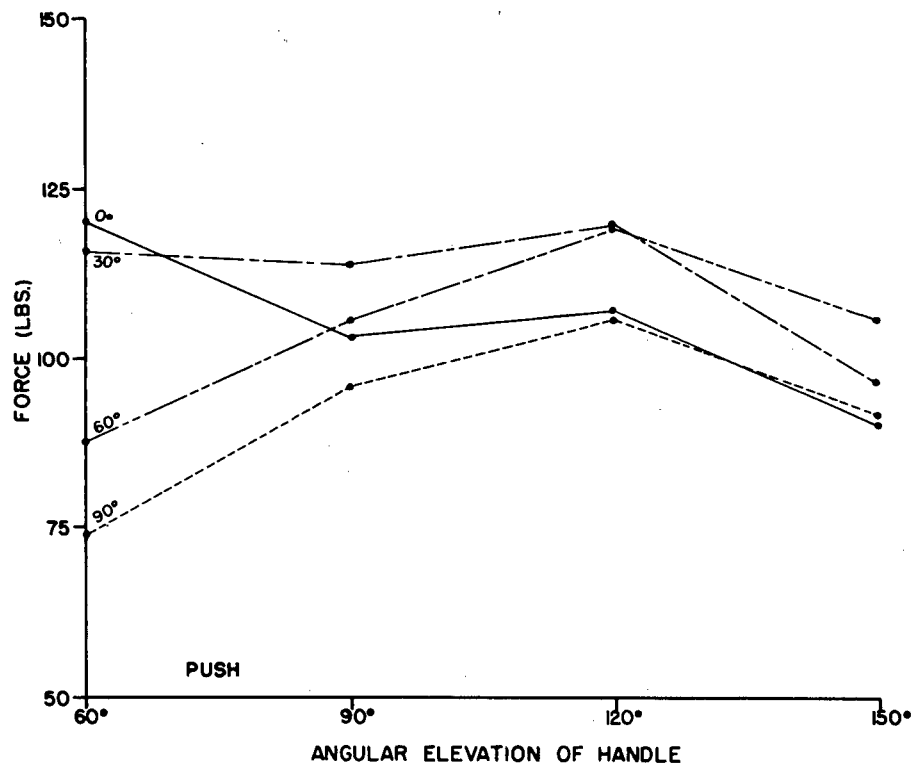
Fig. 13.   Force of push movement at four lateral positions for the four angular elevations of the handle.

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The figure shows what appears to be a strong linear by quadratic inter-action but this was not nearly so strong as the linear by linear inter-action and it did not quite attain significance at the 1% level of confi-dence.

From Figure 13 it is evident that the angular elevation of the handle had relatively little influence on the strength of the push move-ment. However, the F-ratio for "Angular Elevations" was significant at the 1% level of confidence. The data curve had a statistically sig-nificant quadratic component. It is apparent in Table 3 that output in-creased as the handle was elevated from 60° to 120° and that it then de-creased to its lowest point when the elevation was further increased. The mean output at 150° elevation was only 15% less than at 120°.

The comparison of Figure 14 with Figure 13 reveals that the force of the push movement was affected more strongly by the handle distance than by either the angular elevation or the lateral position of the handle. In Table 4 it is shown that the output increased from a mini-mum of 63.6 pounds at the 12-inch distance to a maximum of 130.5 pounds at 24 inches and then decreased at the 28-inch distance. Ac-cording to the analysis of variance the curve fitting the means for the five handle distances has statistically significant linear, quadratic, and cubic components.

The effect of handle distance on output was somewhat different at the various lateral positions of the handle. The F-ratio for the inter-action between "Lateral Angles" and "Handle Distances" was significant at the 1% level of confidence. In Table 2 it may be seen that only the linear by linear interaction attained significance. At the 12-inch and 16-inch handle distances the differences among the mean forces at the various lateral positions were small but when the distance was increased to 20 inches or more marked differences in output were observed. In general, the 30° lateral position of the handle was best and the 90° position poorest. There was no appreciable difference between the forces measured at the 0° and 60° lateral positions except at the 28-inch handle distance. When the handle was in front of the shoulder the 28-inch handle distance was best but at all other lateral positions output was greatest at the 24-inch distance.

A statistically significant F-ratio was obtained, also, for the interaction between "Angular Elevations" and "Handle Distances." In Figure 15 it is shown that at the near control positions the 150° ele-vation was substantially inferior to the others but at the 24-inch and 28-inch distances this elevation was somewhat better than the 60° and 90°
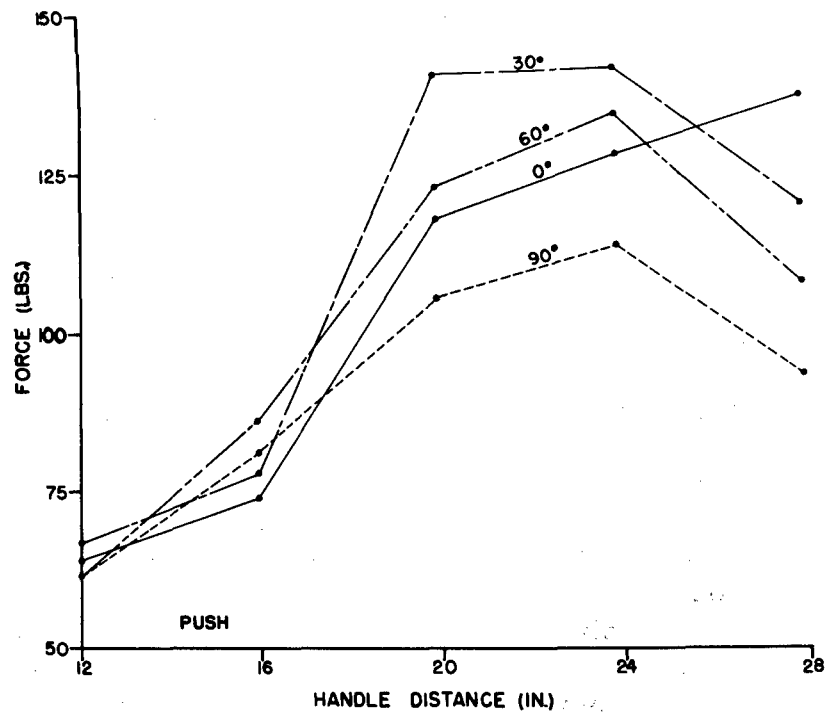
Fig. 14. Force of push movement at four lateral positions for the five handle distances.
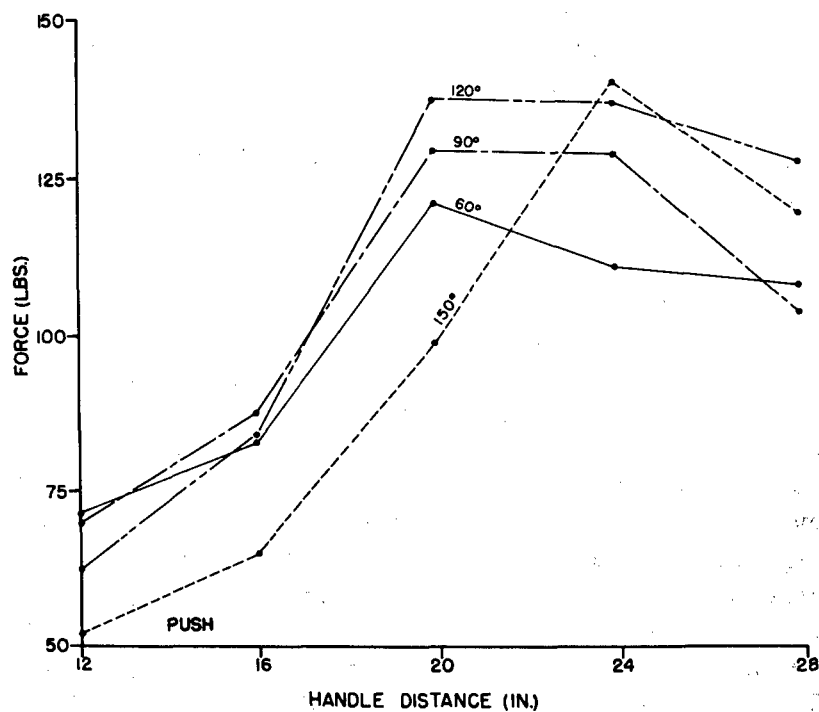

Fig. 15. Force of push movement at five distances for the four angular elevations of the handle.

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elevations. At the 12-inch and 16-inch handle distances it made little difference whether the handle was at the 60°, 90°, or 150° elevations but where the distance was increased to 24 inches or 28 inches the high positions of the handle were most favorable.

F. The Pull Movement

In Table 3 it is shown that the angular elevation of the handle had a statistically significant effect on the strength of the pull movement and that a quadratic curve provided the best fit to the four data points. These results are shown in Figure 16 where it may be seen that this movement tended to be strongest at the 60° and 150° elevations and weakest at the middle elevations. It should be noted in this figure and in Table 2 that there was a linear by linear interaction between "Angular Elevations" and "Lateral Angles." When the quadratic component for "Angular Elevations" was removed from these data it was found that the data for each lateral position could be best approximated by a straight line and that the slope of this line varied with the lateral position of the handle. One may see from the figure that when the handle was at either the 60° or 90° elevation the 0° lateral position was best and the strength of movement decreased progressively as the lateral angle increased. The opposite pattern of results was obtained at the 120° and 150° elevations: that is, output was greatest at the 90° lateral position and it was reduced as the lateral angle decreased. In summary, it may be stated that if the handle is placed at or below the level of the shoulder this movement will be strongest when the handle is located in front of the shoulder, but if the handle is placed at or above 120° elevation it should be positioned at the subject's side.

The effect of handle distance on the strength of the pull movement is evident in Table 5 and Figure 17. In Table 2 it is shown that the F-ratio for "Handle Distances" was significant at well beyond the 1% level of significance and that a straight line provided the best fit to the five means. The output increased with handle distance but the rate of increase was dependent upon the elevation of the handle. This is evidenced by the statistically significant F-ratio for the interaction between "Angular Elevations" and "Handle Distances." The slope of the regression line decreased as the elevation was increased. The difference between the means at the 28-inch and 12-inch handle distances decreased from 39.6 pounds at 60° elevation to 13.0 pounds at an elevation of 150°. It is evident that at the 12-inch and 16-inch handle distances the high (150°) position of the control was most favorable but at the greater distances the low (60°) position was best.
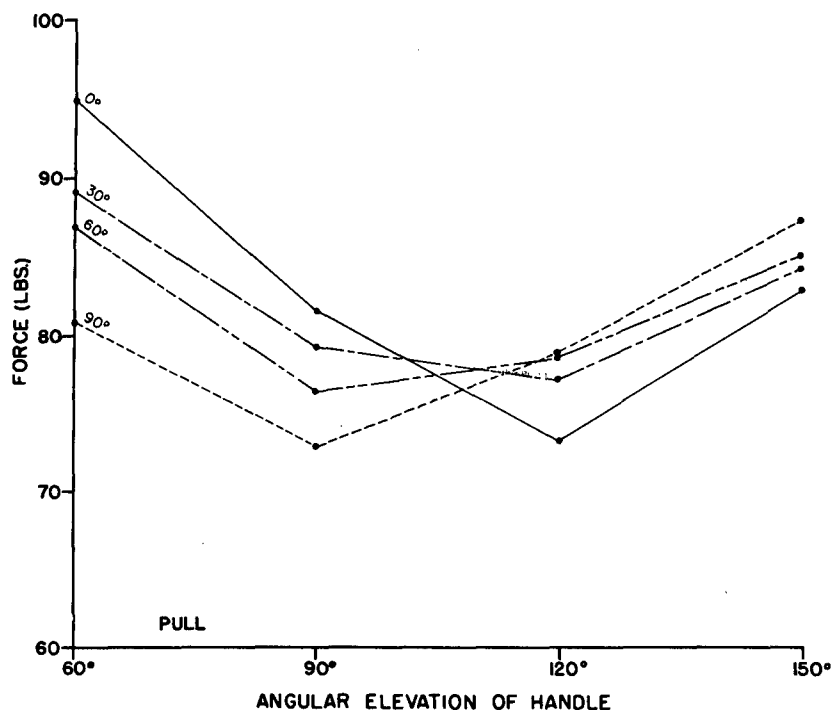
Fig. 16. Strength of pull movement at four angular elevations for the four lateral positions of the handle.
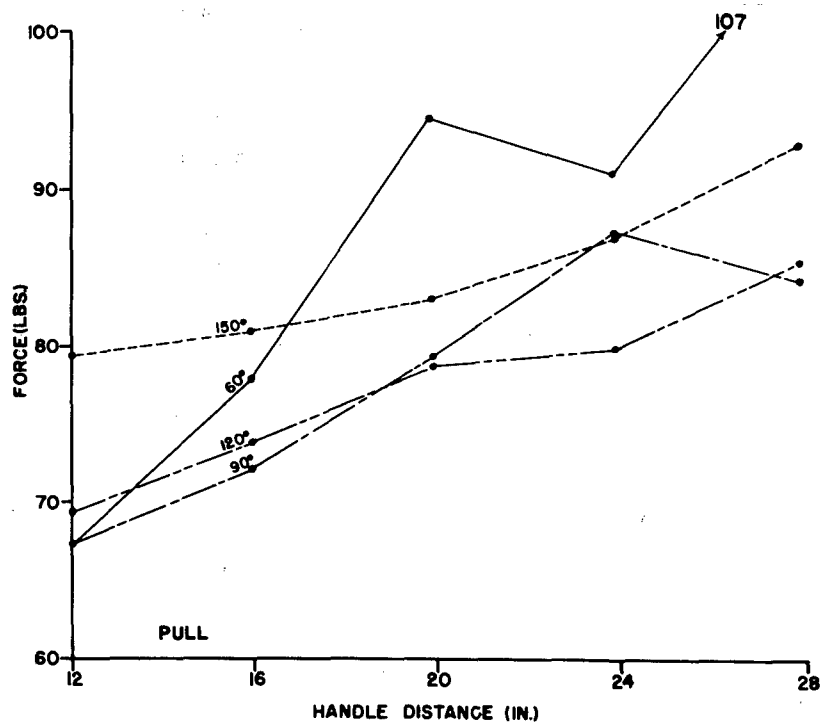

Fig. 17. Strength of pull movement at four angular elevations for the five handle distances.

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G. All Movements

The mean strengths of the movements in order of magnitude were as follows: push, 102.9 pounds; pull, 82.0 pounds; down, 57.7 pounds; left, 32.2 pounds; up, 28.4 pounds; and right, 21.0 pounds. Only in those cases noted below was there any overlap in outputs between movements.

Push was stronger than pull except at some high, near control positions. Pull was stronger than push when the handle was at a distance of 12 inches or 16 inches at the 150° elevation, and when it was at a distance of 12 inches at the 120° elevation.

At several control positions down was stronger than pull. All these positions were at elevations between 90° and 150° and at a distance of not more than 16 inches. Thus, at some high, near positions, the down movement was stronger than either push or pull.

The up movement was stronger than the left movement at a number of positions. The positions in which this occurred were always at distances of 24 inches or 28 inches and at elevations between 90° and 150°. Thus, it may be stated that at the high, far control positions, up tended to be stronger than left.

From Tables 1 and 2 it may be noted that the lateral position of the control had no effect on the up and pull movements. In both cases statistically significant L x E interactions were obtained but these had comparatively little effect on the output. In neither case does this interaction account for a change in output of as much as 2 pounds. This may be seen from the formulae contained in the figures in the Appendix. The strength of the left and right movements decreased with the lateral angle. Down and push were strongest at the 30° lateral position and output decreased as the lateral angle was made either larger or smaller.

The control elevation had no significant effect upon the up and right movements. There was a statistically significant L x E interaction for the right movement but it had little real effect on output. Down and push were strongest at the intermediate elevations and decreased in strength as the extreme elevations were approached. The left movement was strongest at the low control positions and output decreased as the handle was elevated. Pull was stronger at the low or high control elevations than at the intermediate elevations.

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Control distance was the only factor which had a strong effect on all movements. The up, down, left, and right movements all decreased in strength as the control distance increased while the strength of push and pull tended to increase with control distance. It should be noted, however, that push was stronger at the 28-inch distance than at the 24-inch distance.

IV. SUMMARY AND CONCLUSIONS

Five subjects were employed in an investigation to determine the effect of control position on the force with which six linear hand movements could be made along the $\underline{X}$, $\underline{Y}$, and $\underline{Z}$ axes of an essentially isometric control. Measurements were made of the maximum force applied in a 5-second period to a dynamometer handle by each of six linear hand movements. The maximum strength of each movement was measured at 80 control positions: that is at five handle distances, at four angular elevations, and at four lateral positions. The data were analyzed by the method of orthogonal polynomials which, because of its relative unfamiliarity to some psychologists, is explained in some detail in the Appendix. The results for each of the six movements will now be presented in the form of recommendations and summary statements.

A. The Up Movement

1. The optimum elevation of the handle was dependent upon its lateral position. The most favorable position of the handle was in front of the shoulder and at the lowest elevation (60°). When the handle was at the 30° and 60° lateral positions the output was about the same at all elevations, but when it was located at the side the high positions of the handle (120° or 150°) were best. Thus the low, frontal position of the handle is to be preferred, but if the handle must be placed toward the side its elevation should be increased.

2. At all combinations of lateral position and elevation the handle should be close to the shoulder, or at a distance of about 12 inches. The handle distance had a much greater effect on output than did either lateral position or elevation.

B. The Down Movement

1. The handle should be placed near the 30° lateral position but if this is not possible the 60° or 120° are almost as good. In general, elevation had comparatively little effect upon output.

2. At the near (12-inch) control position the handle elevation should be at least 90° and at the far (28-inch) position the elevation should be no higher than 120°. At the intermediate distances the 90° elevation is to be preferred.

3. The handle should be placed about 12 inches from the shoulder. Output will progressively decrease as the handle distance is increased.

4. Thus, the most favorable control location for this movement should be at a lateral position of 30°, an elevation of 90°, and at a distance of 12 inches. Distance is more critical than either of the other two variables.

C. The Left Movement

1. This movement is strongest when the handle is in the low frontal position, or at the 60° elevation in the 0° lateral position. Whatever the lateral angle of the control, the 60° elevation is preferred.

2. If the handle must be placed at the height of the shoulder (90°) or slightly above (120°) its lateral position is relatively unimportant, but if it must be placed in the high (150°) position it should be at or near the subject's side.

3. The control should be placed at a distance of about 12 inches from the operator's shoulder. This distance should be maintained at all combinations of angular elevations and lateral positions of the handle.

4. Taking all the above points into consideration, it may be said that the handle should be located in front of the shoulder at an elevation of 60° and at a distance of 12 inches.

D. The Right Movement

1. In order to maximize the strength of this movement, the control should be located in front of the shoulder. There will be a progressive decrease in strength as the control is positioned farther and farther toward the side.

2. The optimum angular elevation of the control is dependent upon both its lateral position and its distance from the operator. When the control is located in front of the shoulder the 60° elevation tends

to be preferred. At the other lateral positions elevation becomes some-
what less important. When the control is near the shoulder the 150°
elevation is best, but when the distance is increased to about 28 inches
the 60° elevation is best.

3. The control should be placed at a distance of about 12 inches
from the center of the operator's shoulder. The strength of the move-
ment will be reduced substantially if the distance is increased. Control
distance has a greater effect on output than does either of the other vari-
ables.

4. In summary, the handle should be placed in the mid-line
of the shoulder and at a distance of 12 inches. At this combination of
lateral angle and distance the elevation is not so important, but if the
distance must be increased the 60° elevation should be used.

E. The Push Movement

1. The optimum lateral position of the control cannot be stated
without considering both the angular elevation of the control and its
distance from the operator. The greatest output should be obtained when
the control is in the 30° lateral position, at an elevation of 120°, and at
a distance of about 24 inches.

2. At a control distance of 12 inches or 16 inches the output
will be about the same at the 60°, 90°, and 120° elevations and the
lateral position of the control will have little effect on the output.

3. Whenever possible the control should be placed at a distance
of about 24 inches from the operator's shoulder. This should be the
optimum distance regardless of the lateral position or elevation of the
control. At this distance the 120° and 150° elevations are most favorable.

4. If the control cannot be placed near the 30° lateral position
it may be moved out as far as 60° without causing a great decrease in
the operator's output. The control should not be placed at the operator's
side for this is the poorest of all lateral positions.

F. The Pull Movement

1. The optimum elevation of the control for this movement is
dependent upon its lateral position. If the control is placed in front of
the shoulder it should be at an elevation of about 60°. When the control
is located in an intermediate lateral position, between about 30° and 60°,

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it should be placed at an elevation of 60°. If this elevation is not practical then the 150° elevation should be considered next for the output here would be only slightly less than at 60°. If the control must be placed at the side then it should be set at an elevation of 150°.

2. If the control is placed below shoulder level it should be located as close as possible to the mid-line of the shoulder. If the control must be placed well above the shoulder then it should be located near the operator's side.

3. Whatever the elevation or lateral position of the control it should be at a distance of about 28 inches from the center of the operator's shoulder. Output will be substantially reduced as the control distance is decreased.

4. This movement should be strongest when the control is in front of the shoulder at an elevation of 60° and at a distance of 28 inches.

G. All Movements

1. With the exceptions noted below, the order of preference for the movements should be as follows: push, pull, down, left, up, and right.

a. If the control must be located near the operator and well above his shoulder, then pull should be stronger than push.

b. When the control is positioned near the operator and at or above the level of the shoulder, the down movement should be stronger than either push or pull.

c. If the control is located at or above shoulder height and at a distance of 24 inches to 28 inches, the up movement should be slightly stronger than the left movement.

d. If the control is placed in a high position (120° to 150°) and at a distance of 24 inches to 28 inches the up movement should be equal to or slightly stronger than the left movement.

2. The lateral position of the control should have no significant effect on the up and pull movements.

3. The strength of the left and right movements will decrease slightly as the control is located progressively farther toward the side.

4. The down and push movements will be strongest if the control is located about 30° to the right of the mid-line of the shoulder. As the lateral position is increased or decreased there will be a substantial decrease in the strength of these movements.

5. The strength of the up and right movements should not be influenced appreciably by the elevation of the control.

6. If down or push movements are required, the control should be placed at or slightly above the level of the operator's shoulder. Very high or low angular elevations of the control will lead to a substantial reduction in the strength of these movements.

7. Controls that are moved toward the mid-line of the shoulder (left) should be placed at an elevation of about 60°.

8. Controls which an operator must pull toward his body should be located at either low (60°) or high (150°) angular elevations.

9. The up, down, left, and right movements will be strongest at near control positions. For these four movements an increase in the distance of the control will result in a progressive decrease in the strength of movement.

10. The strength of push and pull movements tends to increase as control distance increases. Push will be strongest at a distance of about 24 inches, and pull will be strongest at a distance of about 28 inches.

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APPENDIX

THE METHOD OF ORTHOGONAL POLYNOMIALS

The method of orthogonal polynomials enables one to fit any regression curve of the form $Y = a + bx + cx^2 + -----$. A method is given by Fisher (2) by means of which the fitting of the curve can be carried out in successive stages. That is, by this means one can obtain successively the mean of $\underline{y}$, an equation linear in $\underline{x}$, an equation quadratic in $\underline{x}$, etc. In order to do this he takes $Y = A + B\xi_1 + C\xi_2 + D\xi_3 + -----$, where A is the mean of $\underline{y}$ and ξ_1, ξ_2, ξ_3, etc., are the mutually orthogonal functions of $\underline{x}$ of the first, second, third, etc., degrees, respectively, out of which the regression equation may be built. As each term is added the regression line approaches more nearly the observed values. If there are four values of $\underline{x}$ the curve connecting the four means will be completely described by an equation carried through the third degree; if $\underline{x}$ has five values the curve will be completely described by an equation carried through the fourth degree, etc. In the present case the sources of variation are so numerous that the data were first carried through an analysis of variance. Only the statistically significant terms were included in the equations, the remainder is presumed to be random error. The results for the up movement will be examined in detail in order to explain the nature of the analysis of variance and the means by which the regression equation was derived.

The mean squares in the analysis of variance were obtained by summating the products of the appropriate sums and their corresponding polynomials. Then this value was squared and divided by the number of scores in each sum multiplied by the sum of squares of the polynomials. The formula may be written as follows:

$$SS = \frac{[\Sigma(\Sigma X \xi')]^2}{n\Sigma(\xi')^2}$$

To obtain the mean square of the linear component for "Between Lateral Angles" the sums for the 100 scores at each lateral angle (2880, 2893, 2887, 2680) are multiplied by the polynomials (-3, -1, +1, +3). Now $2880(-3) + 2893(-1) + 2887(+1) + 2680(+3)$ equals -606. Then $-606^2 \div 100 [(-3)^2 + (-1)^2 + (+1)^2 + (+3)^2]$ equals 183.618. The sums of squares for the quadratic and cubic components are obtained in identical fashion using the same sums but with different sets of polynomials. To obtain the sum of squares for an interaction such as the linear x linear interaction for "Lateral Angles" and "Angular Elevations" a 4 x 4 table is set

up and the sum of the scores are entered in the appropriate cells.
These sums are then multiplied by the cross-products of the cor-
responding polynomials. These resultants are summed, squared, and
then divided by the number of scores per cell times the sum of the
squares of the products of the two polynomials. The formula now may
be written:

$$MS_{a_1 \times b_1} = \frac{\Sigma[\Sigma X (\xi'_{a_1} \times \xi'_{b_1})]^2}{n\Sigma(\xi'_{a_1} \times \xi'_{b_1})^2}$$

The sum of squares for the above-mentioned interaction will now be
determined to illustrate the method.

Lateral Angle

		0° (-3)	30° (-1)	60° (1)	90° (3)
Angular Elevation	60° (-3)	909 (9)	726 (3)	719 (-3)	588 (-9)
	90° (-1)	745 (3)	688 (1)	705 (-1)	663 (-3)
	120° (1)	618 (-3)	722 (-1)	747 (1)	715 (3)
	150° (3)	608 (-9)	757 (-3)	716 (3)	714 (9)

The figures in the brackets at the head of each column and to the
left of each row are the linear polynomials, and the figures in brackets
in the cells are the products of the row and column coefficients. Now
990(9) + 745(3) + 618(-3) + 608(-9) + · · · + 714(9) equals 4286, and
$4286^2 \div 25 [(9)^2 + (3)^2 + (-9)^2 + · · · + (9)^2]$ equals 1,836.98.

The statistically significant sources of variation were selected from
the analysis of variance and equations were derived from these which
may be used to "predict" the output of a subject at any combination of
distance, angular elevation and lateral position of the handle. The means
by which an equation was derived will now be explained. From the analy-
sis of variance of the data for the up movement one can see that the
equation must include the mean of the obtained scores, an equation linear
in $\underline{x}$, and one quadratic in $\underline{x}$ for "Handle Distances," and a term for the
linear x linear interaction between "Lateral Angles" and "Angular Ele-
vations." Thus the equation will take the form:

$$\hat{Y} = \bar{Y} + A\left(\frac{D - \bar{D}}{4}\right) + B\left[\left(\frac{D - \bar{D}}{4}\right)^2 - 2\right] + C\left(\frac{L - \bar{L}}{30} \times \frac{E - \bar{E}}{30}\right)$$

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in which $\bar{Y}$ is the mean of the obtained scores, $A(\frac{D - \bar{D}}{4})$ is the linear equation for the "Handle Distances," $B[(\frac{D - \bar{D}}{4})^2 - 2]$ is the quadratic equation for "Handle Distances," and $C(\frac{L - \bar{L}}{30} \times \frac{E - \bar{E}}{30})$ is for the linear x linear interaction. (The 4 appears in the denominator for the two distance terms because the handle distances were 4 inches apart, and 30 appears in both denominators of the interaction because for both the lateral positions and the angular elevations the handle positions were separated by 30°). According to Fisher and Yates (3), "if the regression equation is required in terms of powers of x the formula for the ξ's in terms of powers of x given in Statistical Methods, or the recurrence formula:

$$\xi_{r+1} = \xi_1 \xi_r - \frac{r^2(n'^2 - r^2)}{4(4r^2 - 1)} \xi_{r-1}$$

($\xi_0 = 1$) may be used, together with $\xi' = \lambda\xi$." Now ξ_1 equals $x - \bar{x}$, so $\xi_2 = (x - \bar{x})^2 - 1.25$ when $n' = 4$, as in the case of the "Lateral Angles" and "Angular Elevations;" and when $n' = 5$, as for "Handle Distances," $\xi_2 = (x - \bar{x})^2 - 2$.

The coefficients of the powers of x --A, B, C--are obtained from the formula:

$$A = \lambda \frac{\Sigma(\Sigma X \xi')}{n \Sigma(\xi'^2)}$$

These coefficients may also be obtained from the analysis of variance by dividing the sum of squares by $\Sigma(\Sigma x \xi')$ and multiplying by λ. The value of λ, the coefficient of the highest power of x in ξ', may be obtained from the tables of orthogonal polynomials provided by Fisher and Yates.

The equation for the up movement may now be written:

$$\hat{Y} = 28.35 - 2.58(\frac{D - 20}{4}) + .575[(\frac{D - 20}{4})^2 - 2] + .429(\frac{L - 45}{30} \times \frac{E - 105}{30})$$

By using this equation one can now estimate the strength of the up movement at any handle position in the working area of the right hand.
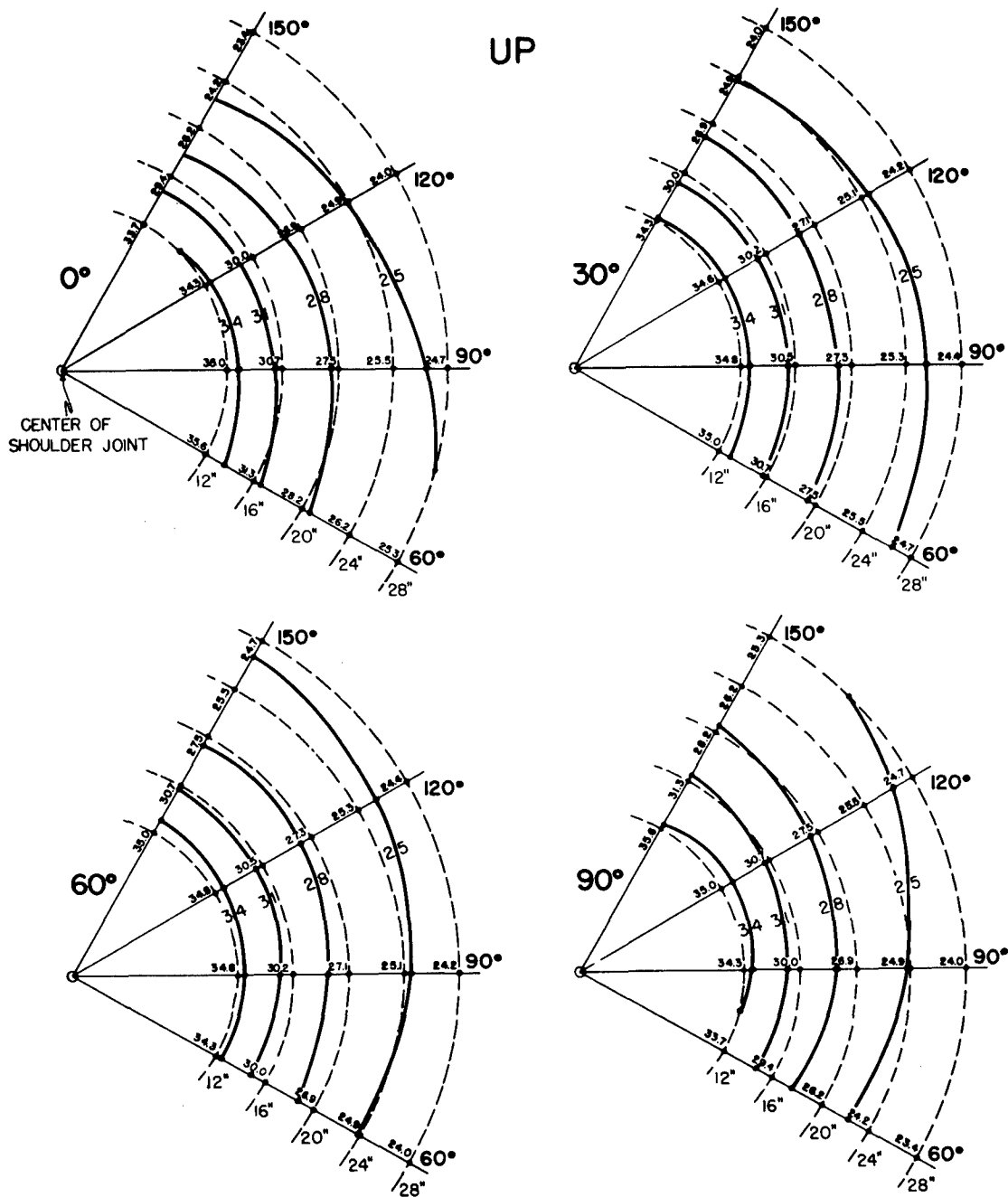
Fig. 1. The 25, 28, 31, and 34 pound isodynes for the up movement
with the mean for each control position derived from the formula:

$$\hat{Y}=28.350-2.580(\tfrac{D-20}{4})+.575\left[(\tfrac{D-20}{4})^2-2\right]+.429(\tfrac{L-45}{30}\times\tfrac{E-105}{30})$$
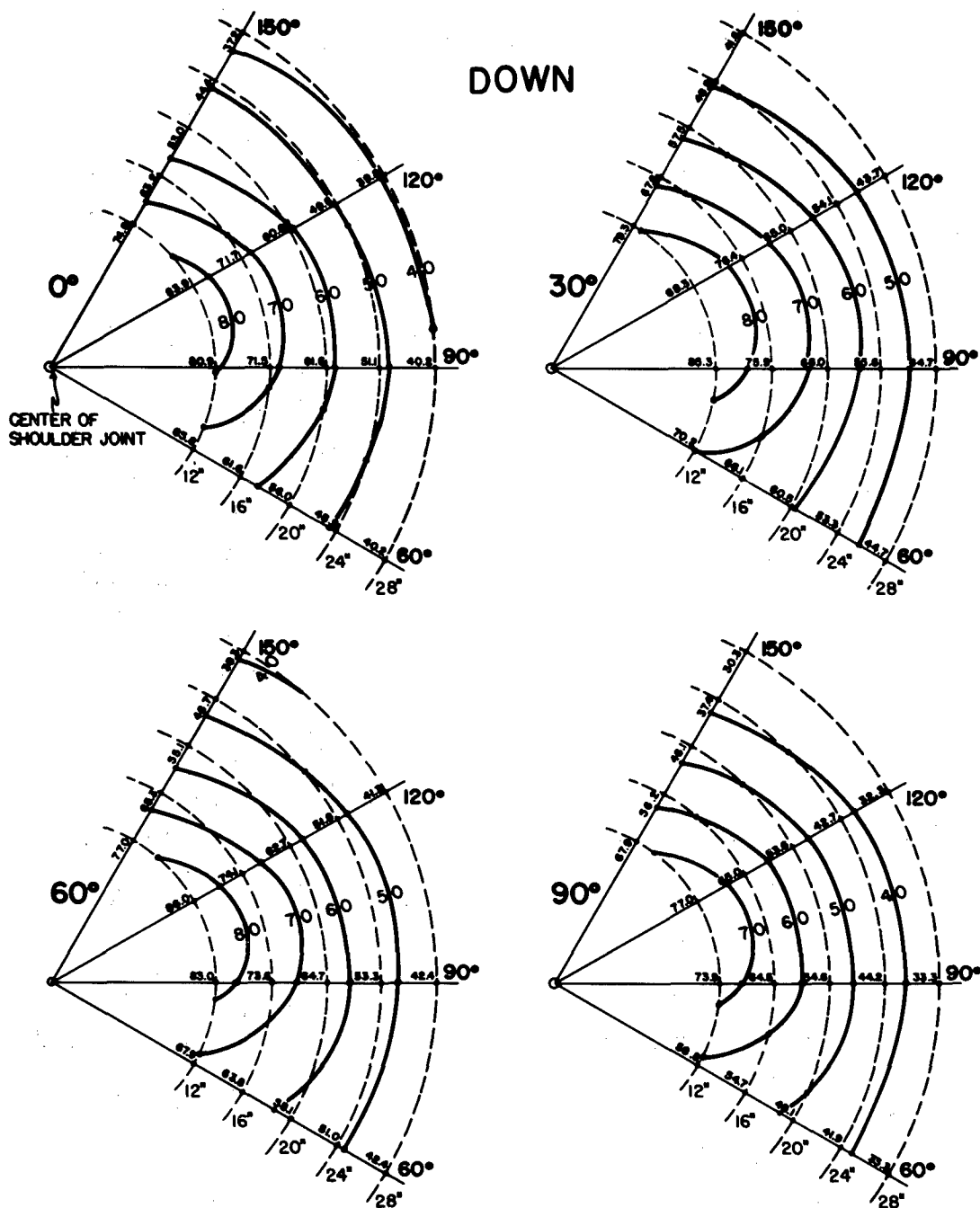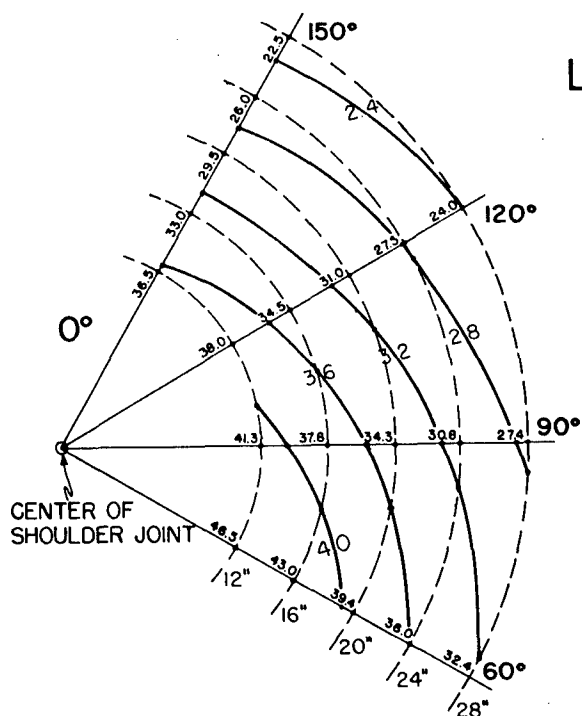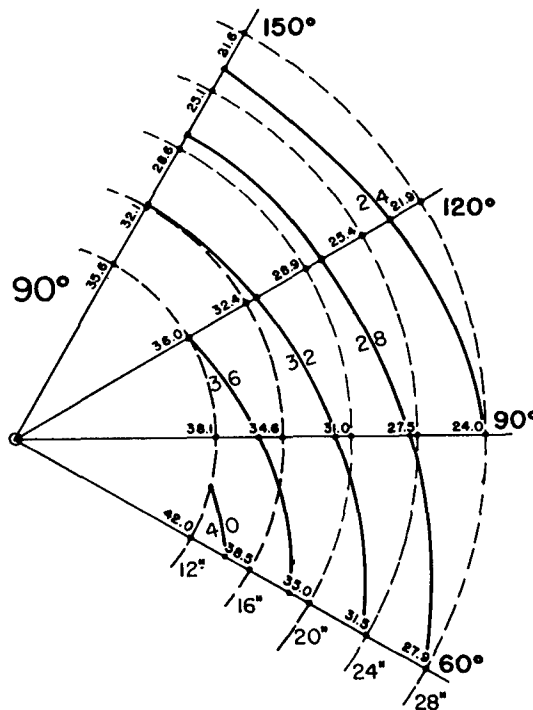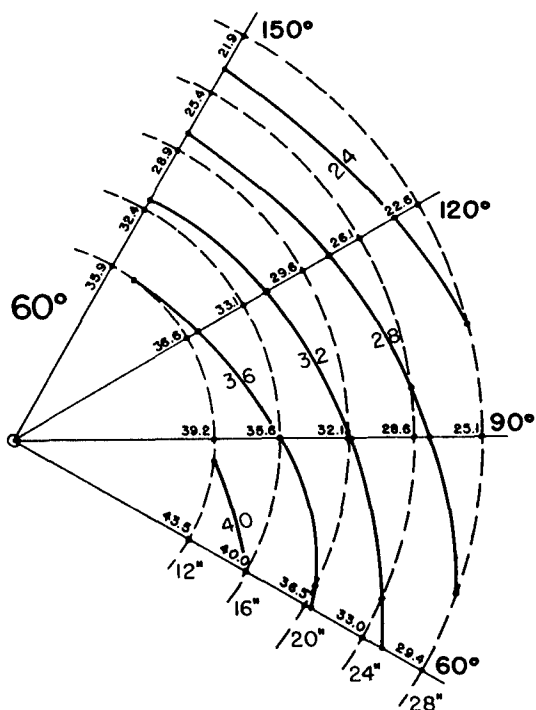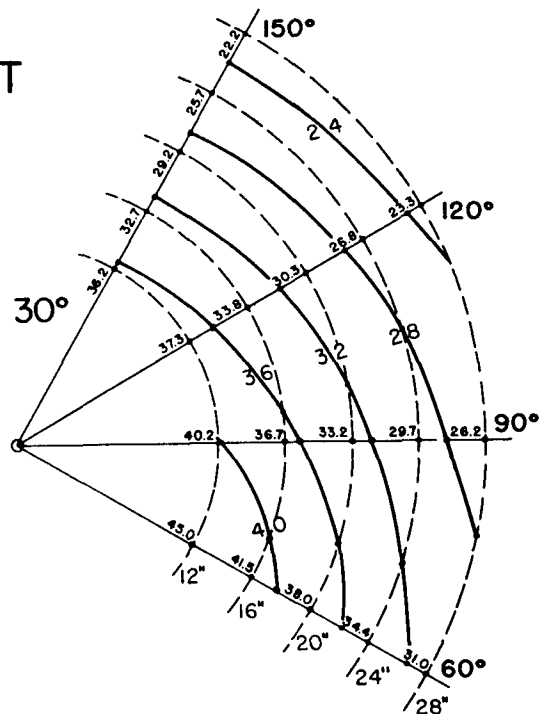
Fig. 2. The 40, 50, 60, 70, and 80 pound isodynes for the down movement with the mean for each control position derived from the formula:

$$\hat{Y} = 57.690 - 2.314\left(\frac{L-45}{30}\right) - 3.385\left[\left(\frac{L-45}{30}\right)^2 - 1.25\right] - 3.265\left[\left(\frac{E-105}{30}\right)^2 - 1.25\right] - 9.280\left(\frac{D-20}{4}\right) - 1.008\left(\frac{E-105}{30} \times \frac{D-20}{4}\right) + .500\left[\frac{E-105}{30} \times \left(\frac{D-20}{4}\right)^2 - 2\right] + 1.384\left[\left(\frac{E-105}{30}\right)^2 - 1.25 \times \frac{D-20}{4}\right]$$

Fig. 3. The 24, 28, 32, 36, and 40 pound isodynes for the left movement with the mean for each control position derived from the formula:

$$\hat{Y}=32.240-.892\left(\tfrac{L-45}{30}\right)-2.714\left(\tfrac{E-105}{30}\right)+.905\left[\left(\tfrac{E-105}{30}\right)^2-1.25\right]-3.509\left(\tfrac{D-20}{4}\right)+.403\left(\tfrac{L-45}{30}\times\tfrac{E-105}{30}\right)$$
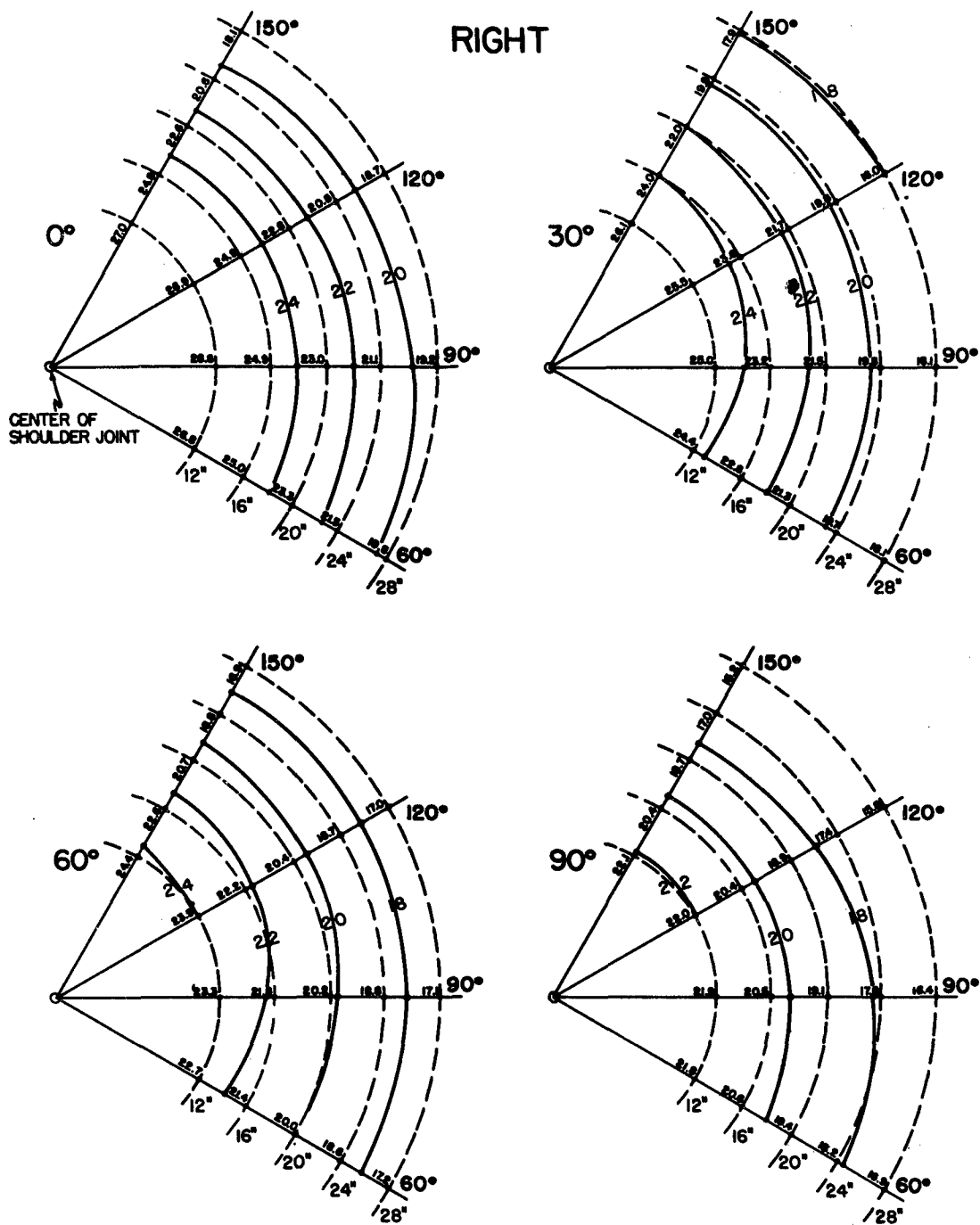
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Fig. 4. The 18, 20, 22, and 24 pound isodynes for the right movement
with the mean for each control position derived from the formula:

$$\hat{Y}=20.970-1.304\left(\tfrac{L-45}{30}\right)-1.719\left(\tfrac{D-20}{4}\right)-.237\left[\left(\tfrac{L-45}{30}\right)^{2}-1.25\times\tfrac{E-105}{30}\right]+.174\left(\tfrac{L-45}{30}\times\tfrac{D-20}{4}\right)-.162\left(\tfrac{E-105}{30}\times\tfrac{D-20}{4}\right)$$
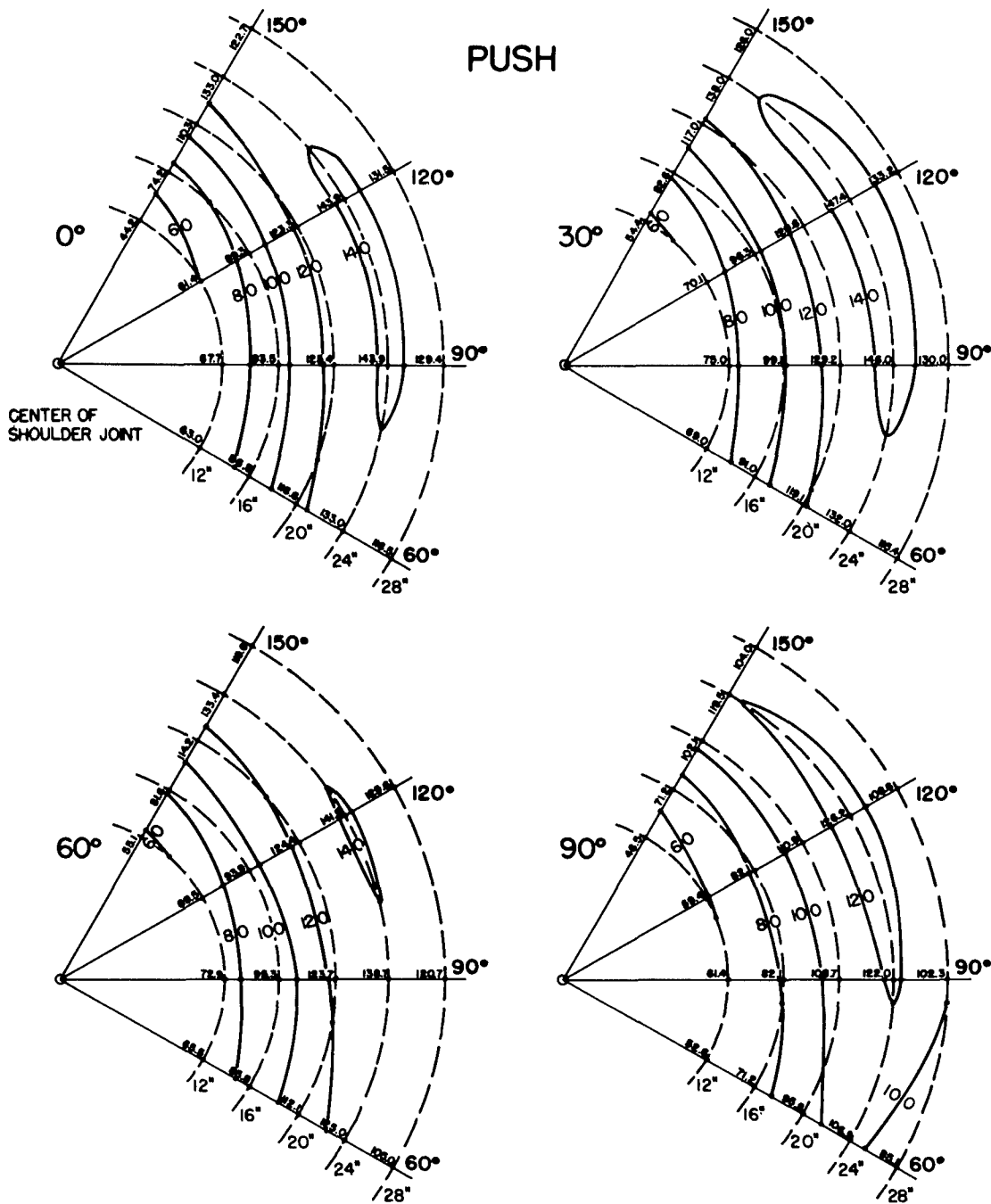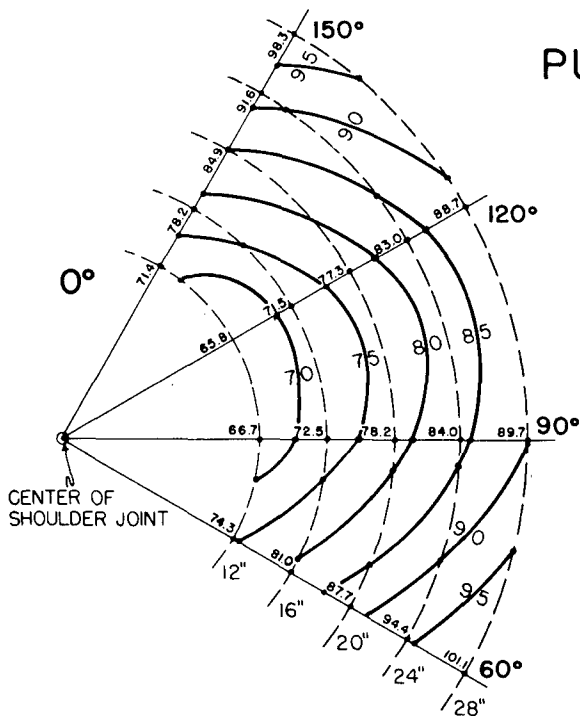
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Fig. 5. The 60, 80, 100, 120, and 140 pound isodynes for the push move-
ment with the mean for each control position derived from the formula:

$$\hat{Y}=102.900-4.852\left(\frac{L-45}{30}\right)-4.698\left[\left(\frac{L-45}{30}\right)^2-1.25\right]-5.442\left[\left(\frac{E-105}{30}\right)^2-1.25\right]+15.818\left(\frac{D-20}{4}\right)-$$

$$6.716\left[\left(\frac{D-20}{4}\right)^2-2\right]-3.899\left\{\left(\frac{D-20}{4}\right)\times\left[\left(\frac{D-20}{4}\right)^2-2\right]-1.4\left(\frac{D-20}{4}\right)\right\}+1.405\left(\frac{L-45}{30}\times\frac{E-105}{30}\right)-$$

$$1.744\left(\frac{L-45}{30}\times\frac{D-20}{4}\right)+2.082\left(\frac{E-105}{30}\times\frac{D-20}{4}\right)$$
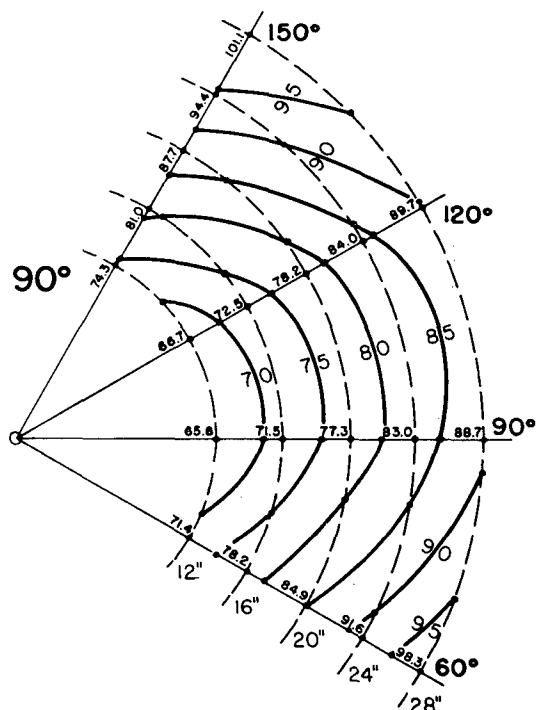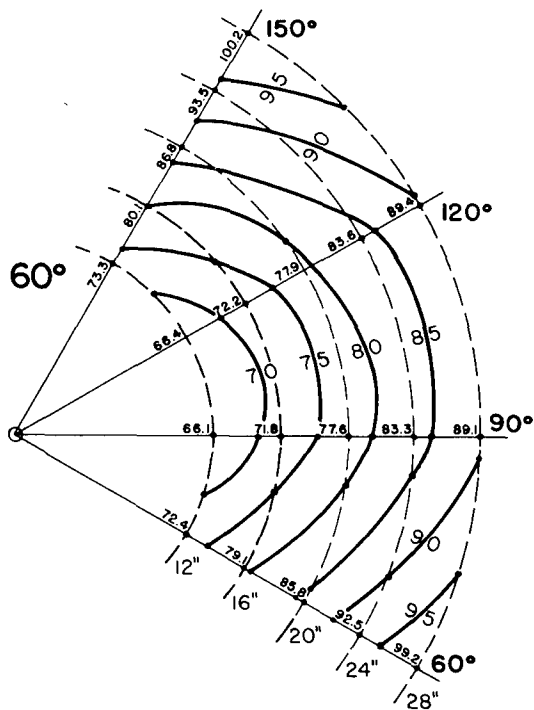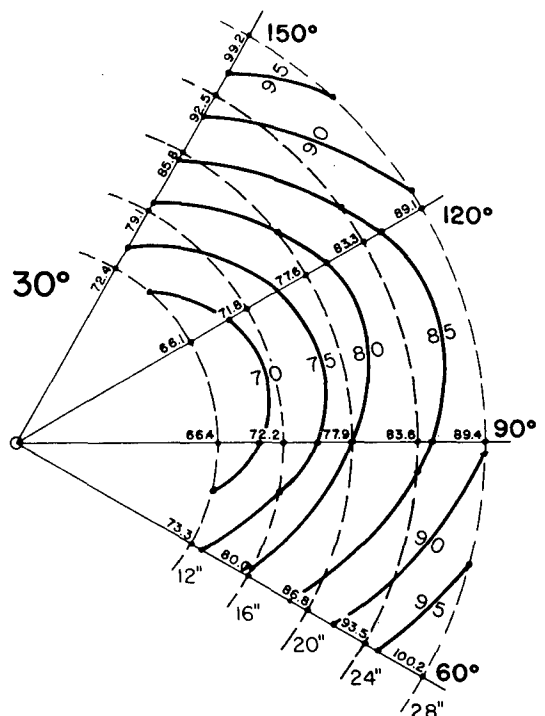
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Fig. 6. The 70, 75, 80, 85, 90, and 95 pound isodynes for the pull movement with the mean for each control position derived from the formula:

$$Y = 82.010 + 4.278\left[\left(\frac{E-105}{30}\right)^2 - 1.25\right] + 5.259\left(\frac{D-20}{4}\right) + .634\left(\frac{L-45}{30} \times \frac{E-105}{30}\right) - .969\left(\frac{E-105}{30} \times \frac{D-20}{4}\right)$$

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